SARGENT, B.P., 2004

THICKNESS OF THE CHICOT AQUIFER SYSTEM SURFICIAL CONFINING UNIT AND LOCATION OF SHALLOW SANDS, SOUTHWESTERN LOUISIANA

STATE OF LOUISIANA

DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

OFFICE OF PUBLIC WORKS AND INTERMODAL

PUBLIC WORKS AND WATER RESOURCES DIVISION

WATER RESOURCES

TECHNICAL REPORT
NO. 73

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Prepared by the

U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

In cooperation with the

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STATE OF LOUISIANA
KATHLEEN BABINEAUX BLANCO, Governor

KAM K. MOVASSAGHI, Secretary
DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

Edmond J. Preau, Jr., Assistant Secretary
OFFICE OF PUBLIC WORKS AND INTERMODAL

Zahir "Bo" Bolourchi, Chief
PUBLIC WORKS AND WATER RESOURCES DIVISION

Cooperative project with the

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

For additional information contact:

Zahir “Bo” Bolourchi, P.E.
Chief, Public Works
and Water Resources Division
Louisiana Department of
Transportation and Development
P.O. Box 94245
Baton Rouge, LA 70804-9245
E-mail: BoBolourchi@dotd.louisiana.gov
Fax: (225) 274-4322
Telephone: (225) 274-4171
Home Page:
www.dotd.louisiana.gov/intermodal/division

Charles R. Demas
District Chief
U.S. Geological Survey
3535 S. Sherwood Forest Blvd., Suite 120
Baton Rouge, LA 70816-2255
E-mail: dc_la@usgs.gov
Fax: (225) 298-5490
Telephone: (225) 298-5481
Home Page: http://la.water.usgs.gov

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Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1927 (NGVD 27).
Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

THICKNESS OF THE CHICOT AQUIFER SYSTEM SURFICIAL CONFINING UNIT AND LOCATION OF SHALLOW SANDS, SOUTHWESTERN LOUISIANA

By B. Pierre Sargent

ABSTRACT

The Chicot aquifer system underlies an area of approximately 9,000 square miles in southwestern Louisiana and is the principal source of fresh ground water in the region. The dense surficial clays that confine the upper sands of the Chicot aquifer system in southwestern Louisiana are known as the Chicot aquifer system surficial confining unit. Although the confining unit may be relatively uniform in composition across large areas, interbedded sands that vary in areal extent and thickness are present within the confining unit. These interbedded sands are collectively known as the shallow sands of the Chicot aquifer system. The shallow sands occur irregularly throughout the confining unit and may be hydraulically connected to underlying aquifers. The shallow sands provide sufficient water for small-diameter wells that supply water for domestic, irrigation, or petroleum rig-supply purposes.

Drillers' logs and geophysical logs were used to define the thickness of the confining unit. The thickness of the surficial confining unit generally increases from north to south. In southern Vernon and Rapides Parishes, where the Chicot aquifer system crops out, the confining unit typically is less than 40 feet thick. The thickness of the confining unit generally increases southward, and generally ranges in thickness from 160 to 400 feet in coastal parishes with a maximum thickness of about 520 feet in Vermilion and St. Mary Parishes.

The locations of wells screened within the surficial confining unit and drillers' or geophysical logs showing shallow sands greater than 10 feet thick are mapped for 12 of the 15 parishes in the study area. The percentage of shallow-sand thickness in the confining unit is indicated for each log. Well-screen depths of 1,579 shallow wells used for domestic, irrigation, or petroleum rig-supply purposes were assumed to indicate the presence of productive shallow sands within the confining unit; however, only about 19 percent of the 2,098 logs analyzed indicate that shallow sands are present. The logs also indicate that the percentage of shallow-sand thickness in the confining unit can vary greatly across very short distances.

INTRODUCTION

Southwestern Louisiana is situated within the Gulf Coastal Plain Physiographic Province. The area is underlain by thick multilayered sequences of unconsolidated sedimentary deposits that alternate among gravel, sand, silt, and clay and that have a predominant dip to the south (U.S. Geological Survey, 1985, p. 229). Areally extensive zones of gravel and sand deposits, which form productive aquifer units, and the adjoining silt and clay deposits, which form confining units, are designated as the Chicot aquifer system (Nyman, 1984, p. 4). The Chicot aquifer system underlies an area of approximately 9,000 mi^2 in southwestern Louisiana (fig. 1) and is the principal source of fresh ground-water in the region (Lovelace, 1999, p. 2). In 2000, almost half of all ground-water withdrawals in Louisiana were from the Chicot aquifer system, and of this amount, more than half of the withdrawals were for rice irrigation (Sargent, 2002, p. 1). Dense surficial clays that overlie and confine the upper sands of the Chicot aquifer system makes the region ideal for rice farming by preventing major water losses through downward seepage (Lovelace, 1999, p. 2). These clays, and thin units of coarser material within the clays are known as the Chicot aquifer system surficial confining unit and will hereinafter be referred to as the confining unit.

The confining unit is composed of both Holocene- and Pleistocene-age sediments and was once thought of as an impermeable barrier to movement of contaminants from the surface to the underlying aquifers (Stanley and Maher, 1944, p. 13; Meyer, 1953, p. 2) (fig. 2). The impermeable barrier assumption has been reconsidered in recent years because of various incidents of subsurface contamination (Trudeau, 1994, p. 2). Hanor (1993) showed that the effective vertical hydraulic conductivity of surficial clay at a hazardous waste disposal site in southeastern Louisiana was as much as four orders of magnitude higher than reported laboratory measurements of clay core samples taken from the site. Hanor attributed the difference to the presence of minor sand beds and to secondary porosity and fracturing that occurred during deposition and sub-aerial weathering of the clay beds. Assuming that confining unit clays in southwestern Louisiana are similar to confining unit clays in southeastern Louisiana, the results of Hanor’s research has implications for clays in the study area. Nyman and others (1990) simulated flow in the Chicot aquifer system and determined that, under 1981 conditions, vertical recharge from the land surface was now occurring throughout most of southwestern Louisiana.

Although the thickness of the confining unit may be relatively uniform across large areas, interbedded sands of varied areal extent and thickness are present within the confining unit. These sands are collectively known as the shallow sands of the Chicot aquifer system. The shallow sands occur irregularly throughout the confining unit and may be hydraulically connected to underlying aquifers. According to State well-registration records, more than 3,000 shallow, small-diameter wells that supply water for domestic, irrigation, or petroleum rig-supply purposes are screened in the shallow sands (Zahir “Bo” Bolourchi, Louisiana Department of Transportation and Development, written commun., 2002).

Little information is available on the thickness of the clay confining unit and the presence of sands within the confining unit; this information could be valuable for making land-use decisions and protecting shallow sources of ground water, as well as the deeper aquifers, from downward-moving contaminants. In 1996, the U.S. Geological Survey (USGS), in cooperation with the Louisiana Department of Transportation and Development (DOTD), began a study to document the thickness and extent of the confining unit and locations of shallow sands within the confining unit.

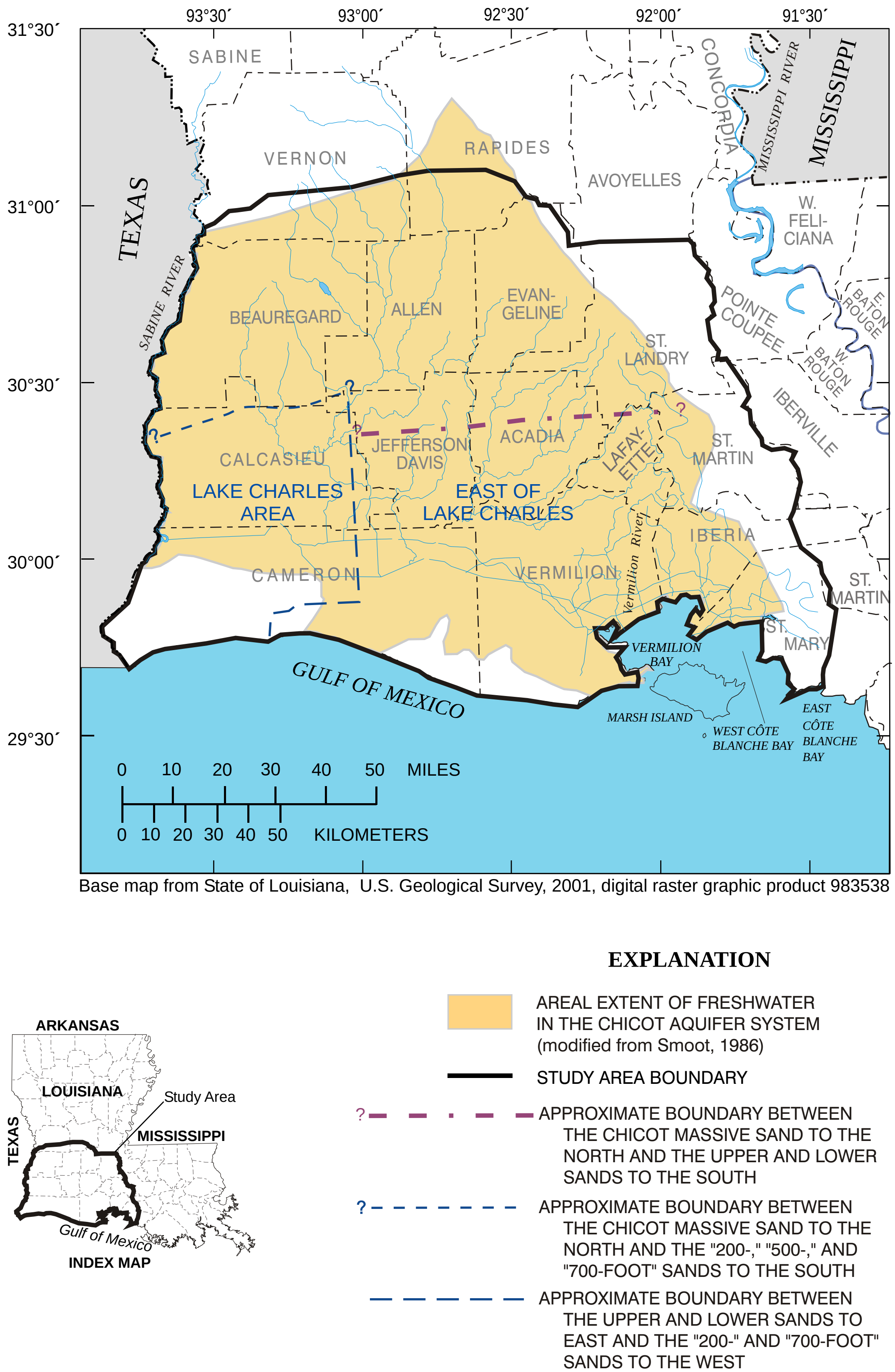

Figure 1. Location of the study area in southwestern Louisiana.

<table>
<tr><th rowspan="4">System</th><th rowspan="4">Series</th><th colspan="3">Hydrogeologic Unit</th></tr>
<tr><th colspan="3">Southwestern Louisiana</th></tr>
<tr><th rowspan="2">Aquifer system</th><th colspan="2">Aquifer or confining unit</th></tr>
<tr><th>Lake Charles Area</th><th>East of Lake Charles</th></tr>
<tr><td rowspan="4">Quaternary</td><td>Holocene (Recent)</td><td rowspan="4">Chicot aquifer system</td><td>Shallow sand or surficial confining unit</td><td>Atchafalaya aquifer, shallow sand, or surficial confining unit</td></tr>
<tr><td rowspan="3">Pleistocene</td><td>"200-foot" sand</td><td>Upper sand</td></tr>
<tr><td>"500-foot" sand</td><td rowspan="2">Lower sand</td></tr>
<tr><td>"700-foot" sand</td></tr>
<tr><td>Tertiary</td><td>Pliocene
Miocene</td><td colspan="3">Evangeline aquifer</td></tr>
</table>

Louisiana Department of Transportation and Development-U.S. Geological Survey Water Resources Cooperative Program

Figure 2. Partial listing of hydrogeologic units in southwestern Louisiana (modified from Lovelace and Lovelace, 1995).

Purpose and Scope

This report documents the thickness of the Chicot aquifer system surficial confining unit and the location of shallow sands within the confining unit. A map is presented that shows the areal pattern of confining unit thickness for all of Acadia, Allen, Beauregard, Calcasieu, Cameron, Jefferson Davis, Lafayette, and Vermilion Parishes and parts of Evangline, Iberia, Rapides, St. Landry, St. Martin, St. Mary, and Vernon Parishes, which are located along the confining unit boundaries. Mapping of small local variations at the base of the confining unit, such as incised-stream channels was beyond the scope of this report.

The location of 2,098 drillers' or geophysical logs, and the percentage of shallow sands within the confining unit (determined from the logs) are shown on maps. The location and depth to the base of well screens of 1,579 domestic, irrigation, or petroleum rig-supply wells that are screened in the shallow sands also are shown. Wells for which log data are available and wells screened in shallow sands often are clustered along roads and in populated areas. Other areas which consist of marsh land or extensive agricultural land far from roads, may have limited amounts of available subsurface information. The quantity and quality of data were insufficient to map the areal extent of individual shallow sand units.

This report provides a basis for collection of more detailed information about the transmissivity of the confining unit and the nature of the interconnection and relation between the confining unit and the deeper hydrogeologic units of the aquifer. Knowledge about the confining unit gained as a result of this study may contribute to the understanding of hydrogeologic conditions of surficial confining units in similar coastal settings.

Description of Study Area

The study area consists of the approximate extent of freshwater in the Chicot aquifer system in southwestern Louisiana (fig. 1). Along the Gulf of Mexico well log information was available that covered Cameron and Vermilion Parishes, so the study area was expanded beyond the areal extent of freshwater in the Chicot aquifer system. Marsh Island, an area in southern Iberia Parish that is mostly marshland bounded by West Côte Blanche Bay to the north and the Gulf of Mexico to the south, was not included in the study area, and no well log information was available. The study area is bounded by the Gulf of Mexico to the south, the Louisiana-Texas State line to the west, and alluvial sediments of the Atchafalaya River to the east. The Chicot aquifer system is cut into or overlain by alluvial sediments of the Atchafalaya River and the exact boundary between the sediments is indistinct. The eastern boundary of the study area, which was based on the presence of available well log information, includes most of Evangeline Parish and parts of Iberia, St. Landry, and St. Martin Parishes. The northern boundary of the study area is located in southern Vernon and Rapides Parishes, where the aquifer system and confining units pinch out near the surface. The existence of well logs also defined the northern boundary of the study area.

Previous Investigations

Previous studies have focused on the ground-water resources of southwestern Louisiana and the occurrence of freshwater in the Chicot aquifer system. Jones and others (1956) mapped the depth to the top of first major sands of the Chicot aquifer system using drillers' logs from water wells and electric logs from petroleum-test holes. The authors also presented detailed textural and lithologic descriptions of the confining unit based on formation samples collected from water-well test holes being drilled by municipalities and private interests during the course of the study.

Jones and others (1956) described two areas where the depth to a major sand is less than 50 ft thick. One area is in southern Vernon and Rapides Parishes, where the Chicot aquifer system crops out, and the other follows the course of the Vermilion River through Lafayette, St. Martin, and Vermilion Parishes. The greatest depth to a major sand described by Jones and others (1956) was more than 700 ft in Cameron Parish. Generally, a uniform depth of about 100 ft to a major sand was indicated throughout most of Evangeline, Jefferson Davis, and Acadia Parishes, western St. Landry Parish, and western Vermilion Parish (Jones and others, 1956, p. 139). Confining unit sediments were primarily attributed to Pleistocene-age back-swamp deposits of the Mississippi and Red Rivers (Jones and others, 1956, p. 82), but also may have included younger overburden sediments near the ground surface.

Harder (1960) mapped the top of the Chicot aquifer in Calcasieu Parish and noted that shallow wells in deposits of Holocene age supply small quantities of water. He stated that, "the exact thickness and areal extent of the sand phase of the Holocene deposits has not been determined; consequently, it is difficult to estimate the hydraulic characteristics and potential yield of these deposits." He also noted that locally there are shallow sands of Pleistocene age, which provide small quantities of water for domestic and stock purposes. Drillers' logs, electrical logs, and aquifer tests were the principal bases for determining the top of the Chicot aquifer.

Whitman and Kilburn (1963) examined ground-water conditions in southwestern Louisiana and discussed the Chicot aquifer along the Gulf of Mexico. Well log information from their report was used in the study described in this report. Harder and others (1967) examined the effects of ground-water withdrawals on water levels and saltwater encroachment in southwestern Louisiana and also provided well log information that was used in this study.

Nyman (1984) mapped the top of the major sands of the Chicot aquifer system, although the focus of the report was the occurrence of high-chloride water in the Chicot aquifer system. Geophysical and driller's logs were used to create the maps. Geohydrologic sections across different parts of the study area also are presented in the Nyman report.

Williams and Duex (1995) presented a map of the top of the upper sand of the Chicot aquifer system in Lafayette Parish and two geologic sections through the parish. Well Lf-488, documented previously by Jones and others (1954), was used as a representative correlation log; and information from the logs of approximately 40 petroleum-wells, 40 municipal water-wells, and several private wells were integrated with sand-analysis reports to produce detailed top-of-sand maps for shallow sand units in Lafayette Parish.

Quaternary Deposition

The geomorphic processes of lateral planation and vertical incision by meandering and braided streams, and eustatic changes in sea level over the last 2 million years produced the deposits that make up the Chicot aquifer system (Kniffen and Hilliard, 1988, p. 35). By reviewing the pattern of Quaternary-age deposition in the study area, a foundation is provided to conceptualize the surface of the base of the confining unit.

Over the last 2 million years, continental ice sheets advanced and retreated at least five times. The melting of the ice sheets, which were north of present day Louisiana, produced glacial streams, which carried an abundance of mineral material through Louisiana on their way to the sea. During each ice advance, the sea level declined and streams began to incise channels until the ice retreated and a corresponding rise in sea level occurred. As the shoreline moved inland the incised channels filled with sediment and the pre-existing surface sediments were reworked. The glacial streams deposited more sediment than they removed, so terraces of fine-grained material were formed over time (Kniffen and Hilliard, 1988, p. 41).

Saucier and Snead (1989) delineated three terrace-like Pleistocene-age sedimentary units near the surface: the Upland, Intermediate, and Prairie Complexes. At land surface, these units have an east-to-west orientation, paralleling the Gulf of Mexico coastline. The Upland Complex is the northernmost band in the study area and consists of fluvial deposits from both glacial and non-glacial sources as well as higher fluvial terraces. South of the Upland Complex, the Intermediate Complex is composed of fluvial deposits of the Mississippi River, its tributaries, and coastal plain streams, and includes terrace deposits. The Prairie Complex is nearest to the Gulf of Mexico and includes the results of a diverse depositional sequence of the Mississippi River, its tributaries, and coastal plain streams. Saucier (1994) listed the major depositional environments for the Prairie Complex as meander belt, Red River deltaic, nearshore marine, and undifferentiated coastal plain. The net result of Quaternary-age deposition in southwestern Louisiana is a great variation in sediment size and distribution throughout the area. As a result, the surface representing the base of the confining unit is assumed to be a composite of multiple discontinuities with depressions and ridges, rather than a flat, continuous sheet. Regionally, however, the slope of this surface generally is to the south, following the orientation of the underlying aquifer units and the overlying land surface.

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The author wishes to thank Flozelle C. Roberts, formerly of the USGS, who assisted in compilation of the well log information, and C. Paul Frederick of the USGS who conducted an initial review of well logs. The Louisiana Department of Natural Resources provided important geophysical information in areas where data were scarce. The author gratefully acknowledges the cooperation of Zahir "Bo" Bolourchi,

Chief of Public Works and Water Resources Division, Louisiana Department of Transportation and Development, for assistance provided during the study and preparation of the report. In addition, Louisiana Department of Transportation and Development provided well-location and well-construction information.

METHODS OF INVESTIGATION

Two sets of data were used in this study. One set included data from geophysical or drillers' logs from selected water wells or test holes. Logs that completely penetrated the confining unit were used to map the thickness of the confining unit and provide information on shallow sands within the confining unit. Data from the 2,098 well logs compiled for this study are presented in a data report by Sargent and others (in press). Well log descriptions, the thickness of the confining unit, and depths to the top and bottom of shallow sands are presented by parish and well identifier in a tabular format. The data report also includes a detailed description of the method used to categorize and compile the log data for this report.

The second set of data included the depth to the base of the screened interval of 1,579 wells, hereinafter referred to as shallow wells, which were screened in the shallow sands and used for domestic, irrigation, or petroleum rig-supply purposes. These data were mapped to indicate the presence of shallow sands. Because shallow wells did not completely penetrate the confining unit or shallow sands within the confining unit, drillers' logs from these wells were not used in this report for mapping the thickness of the confining unit or depths to the top and bottom of shallow sands. Methods used for data compilation, data analysis, and map generation are described in the following sections.

Data Compilation

Drillers' logs and/or geophysical logs with corresponding location information for the well or test hole were compiled into a data set and used to define the depth to the base of the confining unit and identify shallow sands within the unit in southwestern Louisiana. The locations of wells and test holes were obtained as latitude and longitude values from well registration forms. Drillers' logs were available for over 10,000 water wells in the study area. However, the quality and completeness of these logs vary greatly. Drillers collecting lithologic data are mainly concerned with the location of major aquifer units that are capable of supplying long-term yields to wells. When drilling through a thick confining unit, drillers may fail to note lithologic information such as thin sand beds. Therefore, the quality and completeness of each drillers' log was evaluated before it was included in the data set. Drillers' logs that typically used non-geologic terms, such as gumbo or muck, and had lithologic intervals rounded to 100 ft intervals were unacceptable and not used. Drillers' logs that included lithologic descriptions, such as particle size--sand, silt, and clay, with relatively detailed resolution, that is, lithologic intervals rounded to 10 ft intervals or less, were included in the data set.

For water wells for which both a drillers' and geophysical log were available, the driller's and geophysical logs were compared to verify thickness values. In some instances, the geophysical log did not start at the ground surface, and information from both logs was combined to create a composite log. For each location, only one value was designated as the confining unit thickness for that point.

Information from two additional sources also was utilized so that the log data from water-well or test-hole registration forms would not be the sole determinant of confining unit thickness throughout the study area. Geophysical logs from petroleum wells were used in some areas where logs from water wells were sparse or unavailable. Because the first 200 ft below the land surface typically is not logged for petroleum wells, only a small number of these could be used to delineate the thickness of the confining unit. Both drillers' and geophysical log data from published reports also were used. Reports by Jones and others (1956), Harder (1960), Harder and others (1967), Nyman (1984), and Whitman and Kilburn (1963) provided 37, 29, 7, 63, and 4 data points, respectively.

Additional information on the location of shallow sands was obtained from well-screen depths and locational data of 1,579 shallow wells used for domestic, irrigation, or petroleum rig-supply purposes. Screen depths were assumed to indicate the presence of productive shallow sands within the confining unit. This information was obtained from the DOTD well-registration data base. In some instances, a drillers' log may not record the presence of a shallow sand, but a well screened within the confining unit may indicate a shallow sand near that location. The location and depth to bottom of screen of the shallow wells are displayed on maps that also display well logs with shallow sands within the confining unit for comparison purposes. Sand thickness at shallow wells was not assumed equivalent to their screened intervals and was not determined for these wells.

Data Analysis and Map Generation

Depths to the base of the confining unit and shallow sands within the confining unit were determined for each log. The base of the confining unit was identified as the top of first massive sand unit. Massive sand units often were distinguishable not only by thickness, but by coarse basal sediments, which typify sands of the Chicot aquifer system. The thickness of the confining unit was determined by measuring the approximate depth from the ground surface to the top of the massive sand unit. In areas where a massive sand is present within the confining unit, but is directly on top of a Chicot aquifer unit, the thickness was determined from ground surface to the top of the first massive sand. Some previous investigators designated the first sand unit, irregardless as to whether it is a massive sand, as within the confining unit and thus mapped a greater depth to the base of the confining unit.

For example, in Vermilion Parish, a shallow massive sand (formerly called the Abbeville unit) is present within the confining unit (Nyman, 1984, p. 21 and fig. 11). The shallow sand ranges in thickness from 100 to 250 ft and directly overlies what is typically considered the first major aquifer unit of the Chicot aquifer system in this area, the "upper sand" (Nyman, 1984, p. 21 and fig. 11). Because the clay layer separating this sand from the upper sand is thin or missing and this sand is in direct hydraulic communication with the upper sand, the top of this sand was used as the bottom of the clay-confining unit.

Well-log data were grouped by area and the confining unit thickness values were compared for consistency within the area. For instances in which a well log showed an extreme thickness that conflicted with other logs in the same area, the outlier log was deleted from the data set. Although outlier well-log data may be valid, the mapping of local variations in the base of the confining unit, such as those created by the filling of incised channels, was beyond the scope of this report.

The depths to the tops and bottoms of shallow sand units 10 ft or more in thickness were determined from well logs. A shallow sand thickness of at least 10 ft was used to identify possible productive sand units within the confining unit. For each log, the thickness of all shallow sands (10 ft or greater) were totaled and divided by the thickness of the confining unit on the log to determine the percent sand thickness within the confining unit.

All data were entered into a geographic information system (ArcInfo) to analyze the areal distribution of logs and generate maps of the confining unit thickness, the location of wells screened in shallow sands, and the percent sand thickness within the confining unit. To generate the map of confining unit thickness, a statistically-based interpolation method, kriging, was used. Kriging provides an exact interpolation at points where data are provided, is particularly applicable for making estimates where few data points exist, and provides error estimates (Dunlap and Spinazola, 1984, p. 5). The spatial pattern of wells in the study area is such that wells are clustered in some areas, but absent in others. Drilling of new wells was beyond the scope of this study; therefore, kriging was an appropriate interpolation tool for estimating the confining unit thickness in areas were data were sparse or absent.

The thickness of the confining unit was then contoured using a 40-ft contour interval in most areas. In some coastal areas where data were sparse and the confining unit thickens rapidly, an 80-ft contour interval was used. The accuracy of the confining unit thickness contours is a function of the quality and density of the data and the power of the interpolation technique (Burrough and McDonnell, 1998). The estimated error at any point on the thickness map is plus or minus 24 ft.

The locations of wells screened in shallow sands and logs showing the percent sand thickness within the confining unit of individual parishes also were mapped. For mapping purposes, the depth to the base of the well screen was used to indicate the depth of a sand. The base-of-screen depths were grouped in intervals of less than 50 ft, 50 to 100 ft, 100 to 200 ft, and greater than 200 ft. Wells screened in shallow sands often were clustered in population centers. Many of the clustered wells were screened at a similar depth, indicating the presence of a productive sand. In some areas, wells were screened at many different depths, indicating the presence of multiple shallow sands in the area.

The percentage thickness of shallow sands within the confining unit was computed from well logs with a sand interval greater than 10 ft. Where present, percentages were grouped in intervals of 1 to 20, 20 to 40, 40 to 60, 60 to 80, and 80 to 100 percent. Only about 19 percent of the logs indicated shallow sands were present, and the percent sand thickness varied greatly across very short distances. Wells with drillers' log data showing as much as 60 percent sand and shallow wells screened in shallow sands, were often surrounded by wells with drillers' logs that did not encounter sand. These variations may be indicative of the intermittent nature of the shallow sands, but may also illustrate differences in drillers' interpretations that were recorded on logs.

Because of poor areal distribution of well data, the varied quality of the log data, and the intermittent nature of the shallow sands, the areal extents of individual shallow sands could not be mapped. Similarly, the presence or absence of shallow sands could not be inferred for areas where well or log data are sparse or absent.

THICKNESS OF THE CHICOT AQUIFER SYSTEM SURFICIAL CONFINING UNIT

In the study area, the thickness of the Chicot aquifer system surficial confining unit ranges from less than 40 ft along the northern boundary to 520 ft in the southeastern part of the study area, along the Gulf of Mexico (fig. 3). In general, the confining unit thickens southward as its base dips toward the Gulf, conforming to the orientation and dip of the underlying aquifers (Walters, 1996, sheet 1). An exception to the southward thickening occurs in parts of Vermilion and Lafayette Parishes, along the approximate route of the Vermilion River (fig. 1), where the confining unit thins to between 40 and 80 ft thick (fig. 3). This may be evidence of an ancestral Mississippi River floodplain or delta (Kniffen and Hilliard, 1988, map 14). A few miles southeast of this area, the confining unit thickens rapidly to its greatest thickness around the southern part of Vermilion Bay and at points along the coast of East and West Côte Blanche Bays (fig. 3).

LOCATION OF SHALLOW SANDS WITHIN THE SURFICIAL CONFINING UNIT

The presence of shallow sands was documented in 12 of the 15 parishes in the study area. In the remaining three parishes, Vernon, Rapides, and St. Martin Parishes, well-log data indicated no sand intervals greater than 10 ft thick. Table 1 lists descriptive statistics by parish from rural-domestic water-supply wells screened in the shallow sands, including the total number of wells, range of depths to base of well screen, and mean depths to base of well screen. Table 1 also lists descriptive statistics by parish from

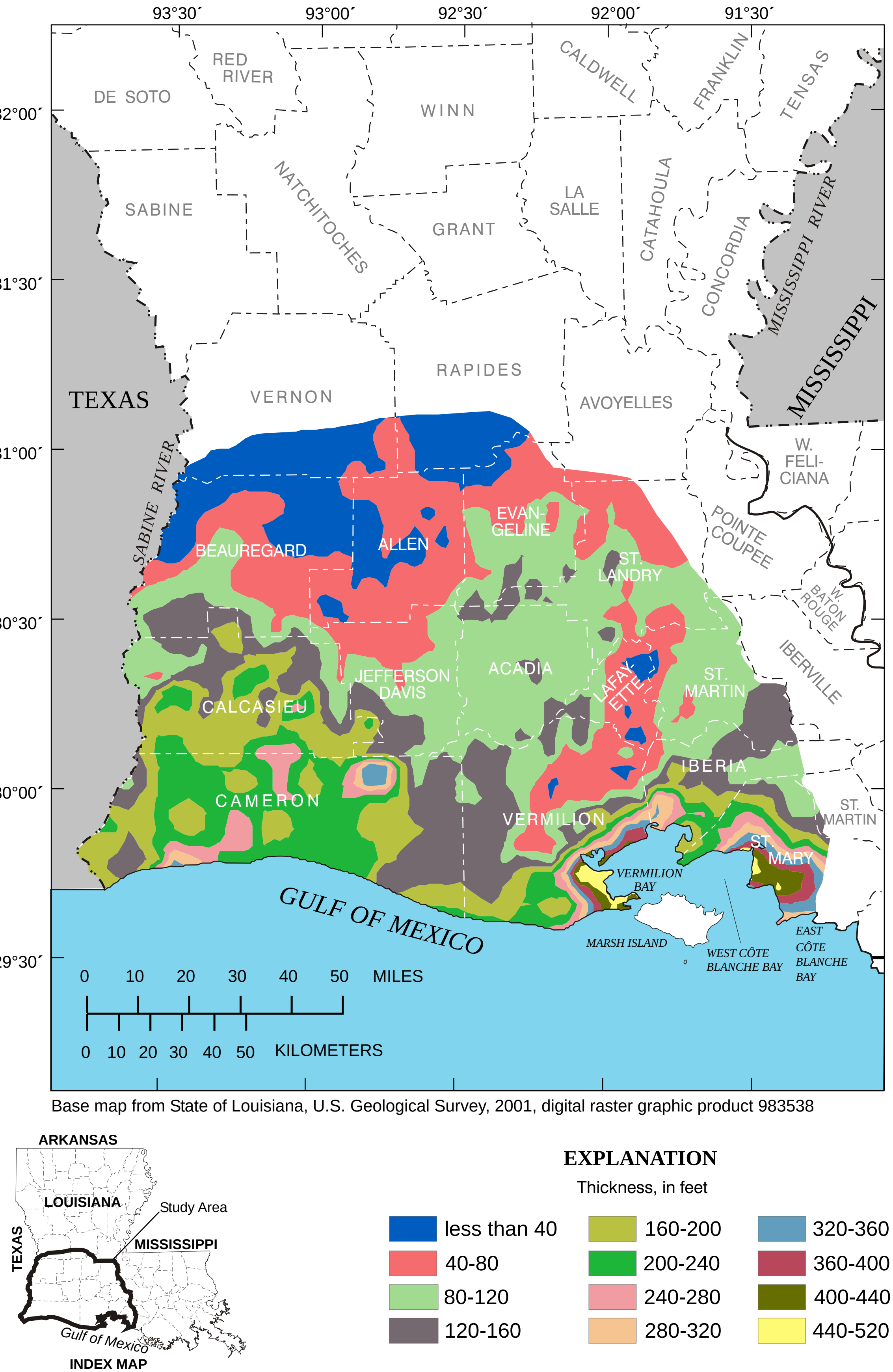


Figure 3. Thickness of the Chicot aquifer system surficial confining unit, southwestern Louisiana.

well logs including total number of well logs, percentage of logs with shallow sands (sand intervals 10 ft or greater), the range and mean depths to the base of shallow sand intervals, the range and mean of shallow sand interval thickness, and the range and mean of percent shallow sand thickness of the confining unit.

A generalized east-to-west hydrogeologic section of the Chicot aquifer system surficial confining unit in northern Acadia Parish shows the location of shallow sands and wells screened within the confining unit (fig. 4). If the section is typical of the confining unit, sand and screen data indicate sands generally are not areally extensive, and may occur at various depths. Also, sand units 10 ft or greater in thickness generally constitute a small part of the confining unit. The well logs indicating no sands may be due to the actual absence of sand or the variability of drillers' interpretations of the confining unit sediments. Figures 5 through 16 show locations of well logs and wells screened in shallow sands, and the percent sand thickness within the confining unit in each of the 12 parishes.

Table 1. Descriptive statistics of the depth of wells screened in the Chicot aquifer system surficial confining unit and well logs in southwestern Louisiana

	Wells screened in surficial confining unit			Well logs (drillers' and geophysical)								
		Depth to base of screen				Depth to base of shallow sands		Thickness of shallow sands		Percentage of shallow sands[2]	
Parish	Total number	Range (feet)	Mean (feet)	Total number of logs	Logs with shallow sands[1] (percent)	Range (feet)	Mean (feet)	Range (feet)	Mean (feet)	Range (feet)	Mean (feet)
Acadia	80	16-103	39	344	9	13-130	67	10-55	23	6-62	21
Allen	6	17-40	27	101	7	15-50	34	10-46	19	15-73	35
Beauregard	63	14-46	34	61	13	26-90	50	10-37	21	8-61	32
Calcasieu	786	4-250	63	242	42	18-247	96	10-110	35	4-71	18
Cameron	101	7-325	127	97	24	24-272	165	15-107	49	5-71	25
Evangeline	42	18-75	35	140	23	15-143	96	10-92	30	7-67	25
Iberia	59	13-270	86	93	19	35-344	116	10-60	19	3-23	12
Jefferson Davis	69	11-210	66	250	13	18-129	80	10-90	34	3-81	34
Lafayette	73	5-116	36	148	14	30-132	71	10-95	23	11-68	26
St. Landry	45	12-110	27	204	18	18-144	85	10-107	39	7-82	36
St. Mary	11	10-326	183	32	19	140-259	170	17-82	38	6-41	18
Vermilion	244	12-350	98	225	27	22-280	99	10-120	37	8-82	32

[1] Percentage of logs with sand intervals of 10 ft or greater.

[2] Percentage of confining unit composed of sand.

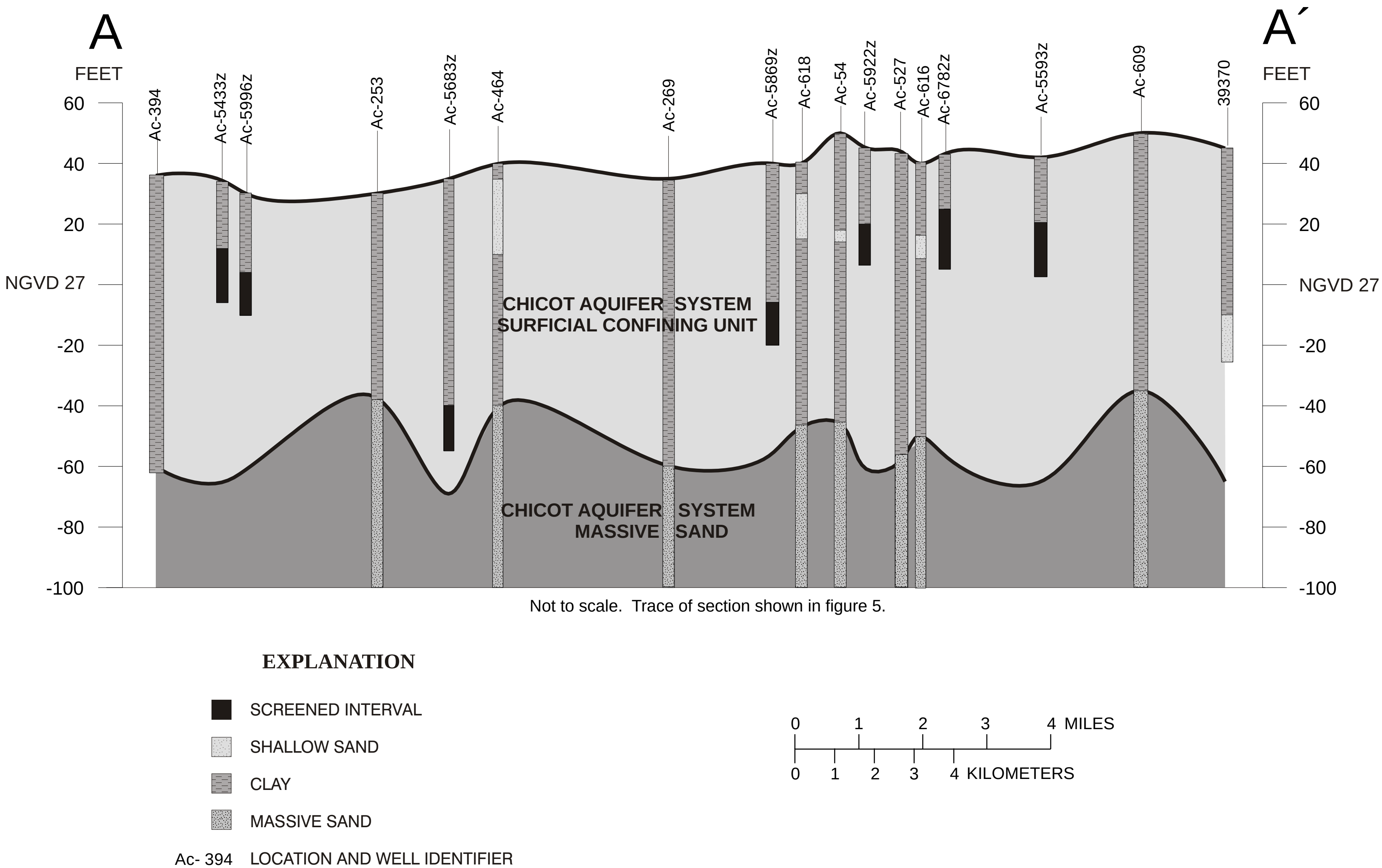


Figure 4. Generalized east-to-west hydrogeologic section in northern Acadia Parish, Louisiana.

In Acadia Parish, wells screened in shallow sands are mostly located in the northern half of the parish and are screened at depths less than 50 ft (fig. 5). Well screen depths range from 16 to 103 ft, with a mean depth of 39 ft (table 1). Five of the 80 wells had screen depths than ranged from 90 to 103 ft; the other 75 wells had screen depths that ranged from 16 to 40 ft. Approximately 9 percent of the 344 selected well logs, which were distributed throughout the parish, showed shallow sands. Well logs showing shallow sands also were mostly in the northern half of the parish.

In Allen Parish, six wells screened in shallow sands are clustered in the Oakdale area. Well screens for all the shallow wells are less than 50 ft deep (fig. 6). Well screen depths range from 17 to 40 ft, with a mean depth of 27 ft (table 1). Of 101 well logs distributed throughout the parish, only 7 percent had shallow sands. These well logs appear to be randomly distributed throughout the parish.

In Beauregard Parish, wells screened in shallow sands are clustered in the DeRidder area. Well screens for all the shallow wells are less than 50 ft deep (fig. 7). Well screen depths range from 14 to 46 ft, with a mean depth of 34 ft (table 1). Well logs in Beauregard Parish have a dispersed areal distribution. Only eight logs, mostly from wells located in the western half of the parish, indicate that shallow sands are present (fig. 7). The scarcity of shallow wells and well logs with shallow sands may indicate that shallow sands have a limited presence in the confining unit in Beauregard Parish.

In Calcasieu Parish, shallow wells screened in shallow sands are located throughout the parish. Well screens for the shallow wells vary in depth from less than 50 ft to greater than 200 ft in depth (fig. 8). Well screen depths range from 4 to 250 ft, with a mean depth of 63 ft (table 1). Fifty-five percent of the wells screened in shallow sands are screened at depths less that 50 ft, but there also are many wells screened between 50 and 200 ft (fig 8). Well logs showing shallow sands in Calcasieu Parish follow the areal distribution of the shallow wells - grouped in a line along the western border, clustered in the east-central part of the parish and scattered elsewhere. Of all of the parishes in the study area, Calcasieu Parish had the greatest percentage (42 percent) of logs showing shallow sands.

In Cameron Parish, shallow wells screened in shallow sands are located along the southern and northern border of the parish. Well screens for the shallow wells vary in depth from less than 50 ft to greater than 200 ft in depth (fig. 9). Well screen depth ranges from 7 to 325 ft with a mean depth of 127 ft (table 1). Well logs showing shallow sands generally are located near shallow wells screened in shallow sands. Few well logs and shallow wells are present in an east-to-west band through the middle of the parish, and it is not known whether shallow sands are present in this area.

In Evangeline Parish, wells screened in shallow sands are located in the southern half of the parish. Well screens for the shallow wells vary in depth from less than 50 ft to 100 ft in depth (fig. 10). Well screen depths range from 18 to 75 ft, with a mean depth of 35 ft (table 1). Most of the well logs with shallow sands also are located in the southern part of the parish. Few well logs and the absence of wells screened in shallow sands in the northern half of the parish indicate few shallow sands are present in that area.

In Iberia Parish, wells screened in shallow sands mostly are located in the western half of the parish. Eastern Iberia Parish is swampy and relatively uninhabited, so there are few rural domestic water-supply wells or well logs. Well screens for the shallow wells vary in depth from less than 50 ft to greater than 200 ft (fig. 11). Well screen depths range from 13 to 270 ft, with a mean depth of 86 ft. Well logs showing shallow sands often were located near shallow wells.

In Jefferson Davis Parish, wells screened in shallow sands are located along the southern, southwestern, and eastern borders of the parish and are absent from the south-central and northern parts of the parish. Well screens for the shallow wells vary in depth from less than 50 ft to greater than 200 ft (fig. 12). Well screen

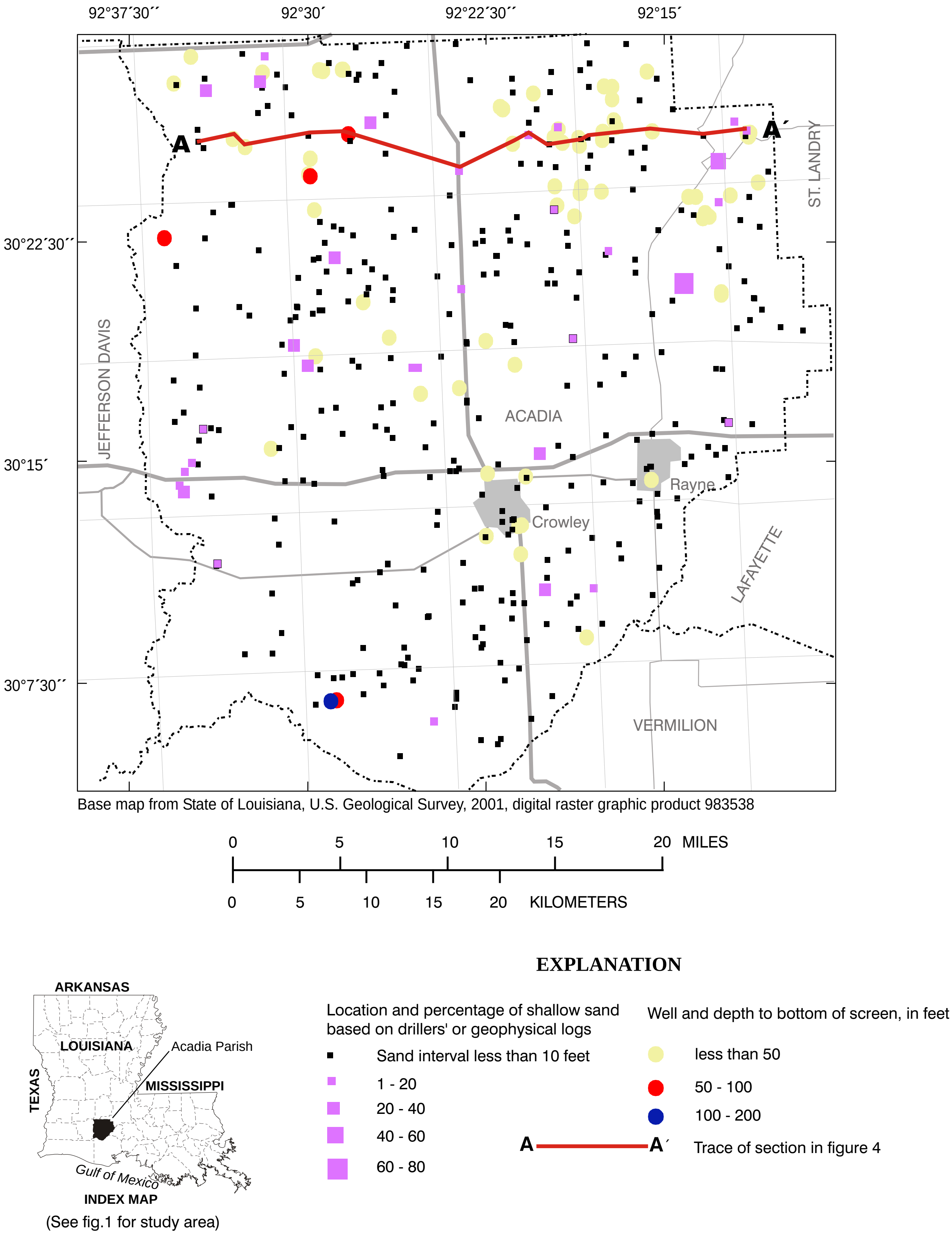


Figure 5. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Acadia Parish, southwestern Louisiana.

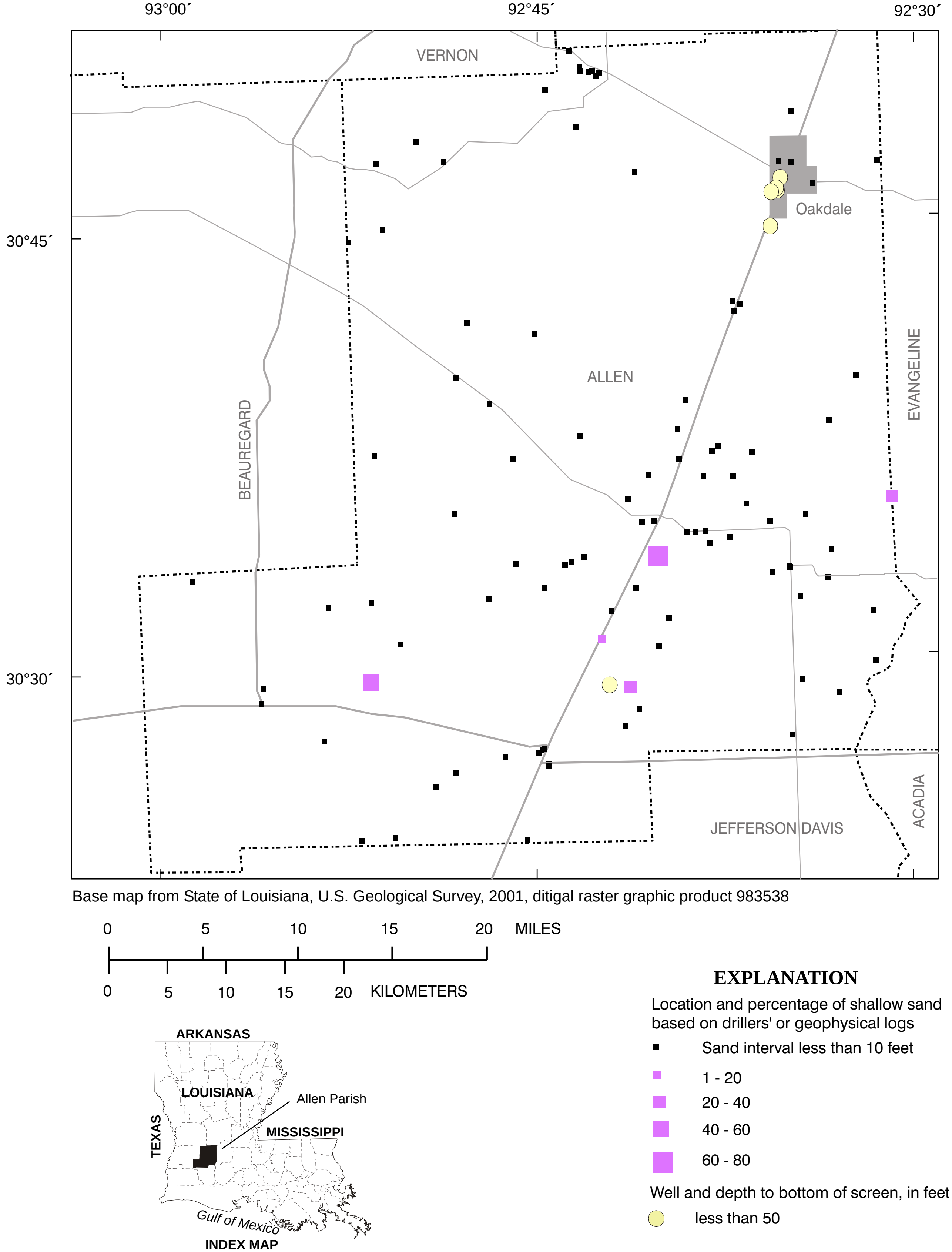


Figure 6. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Allen Parish, southwestern Louisiana.

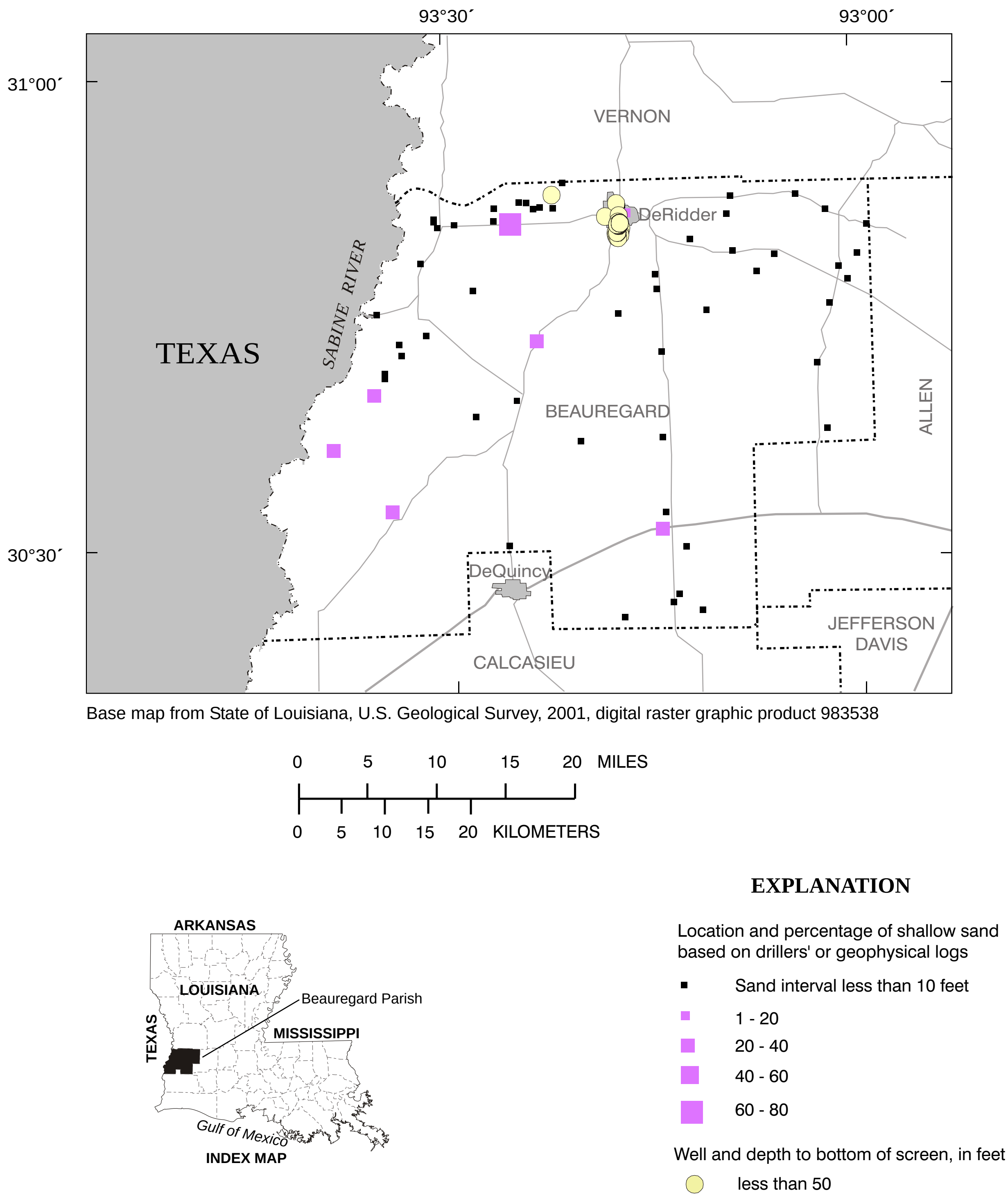


Figure 7. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Beauregard Parish, southwestern Louisiana.

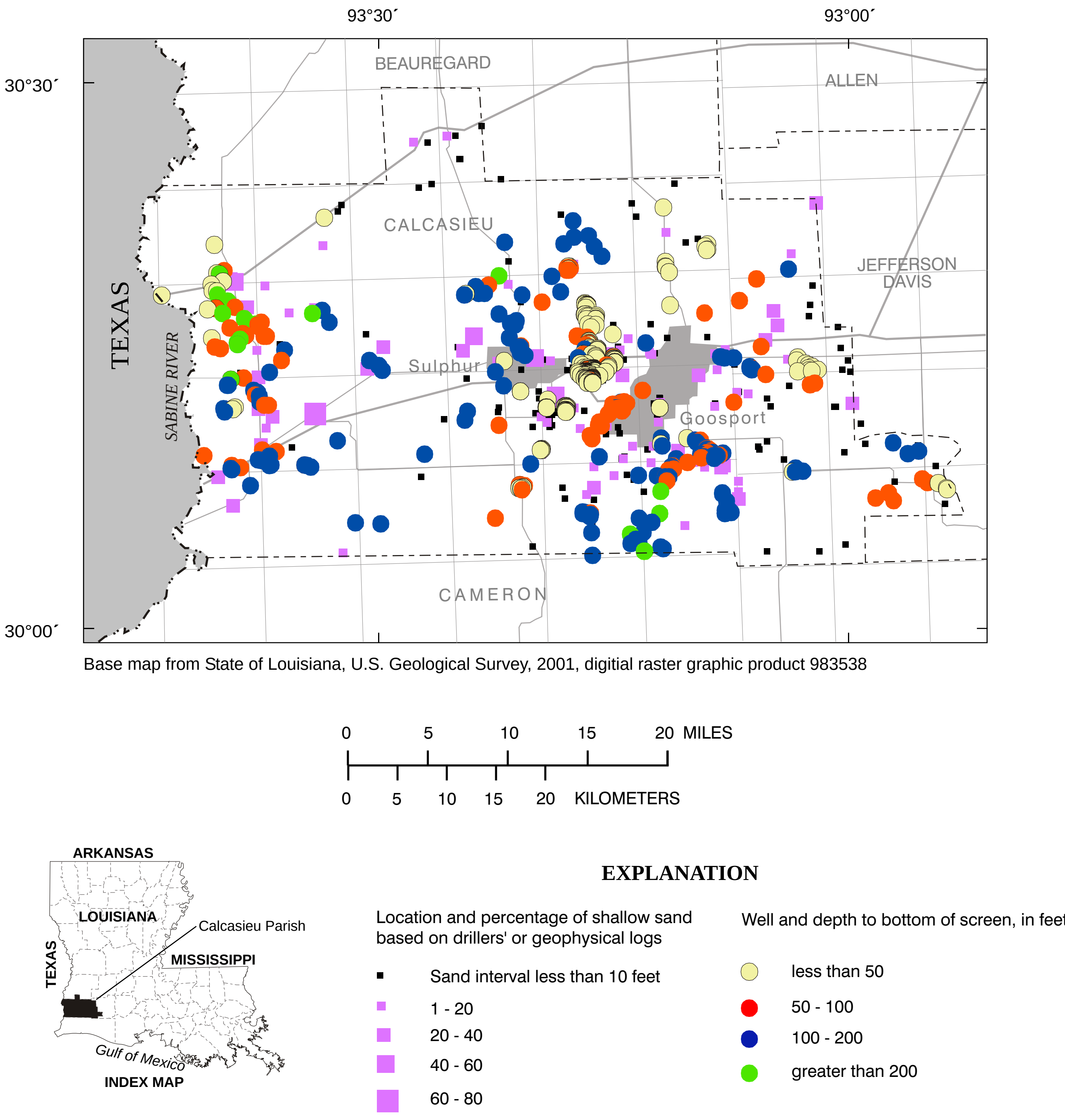


Figure 8. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Calcasieu Parish, southwestern Louisiana.

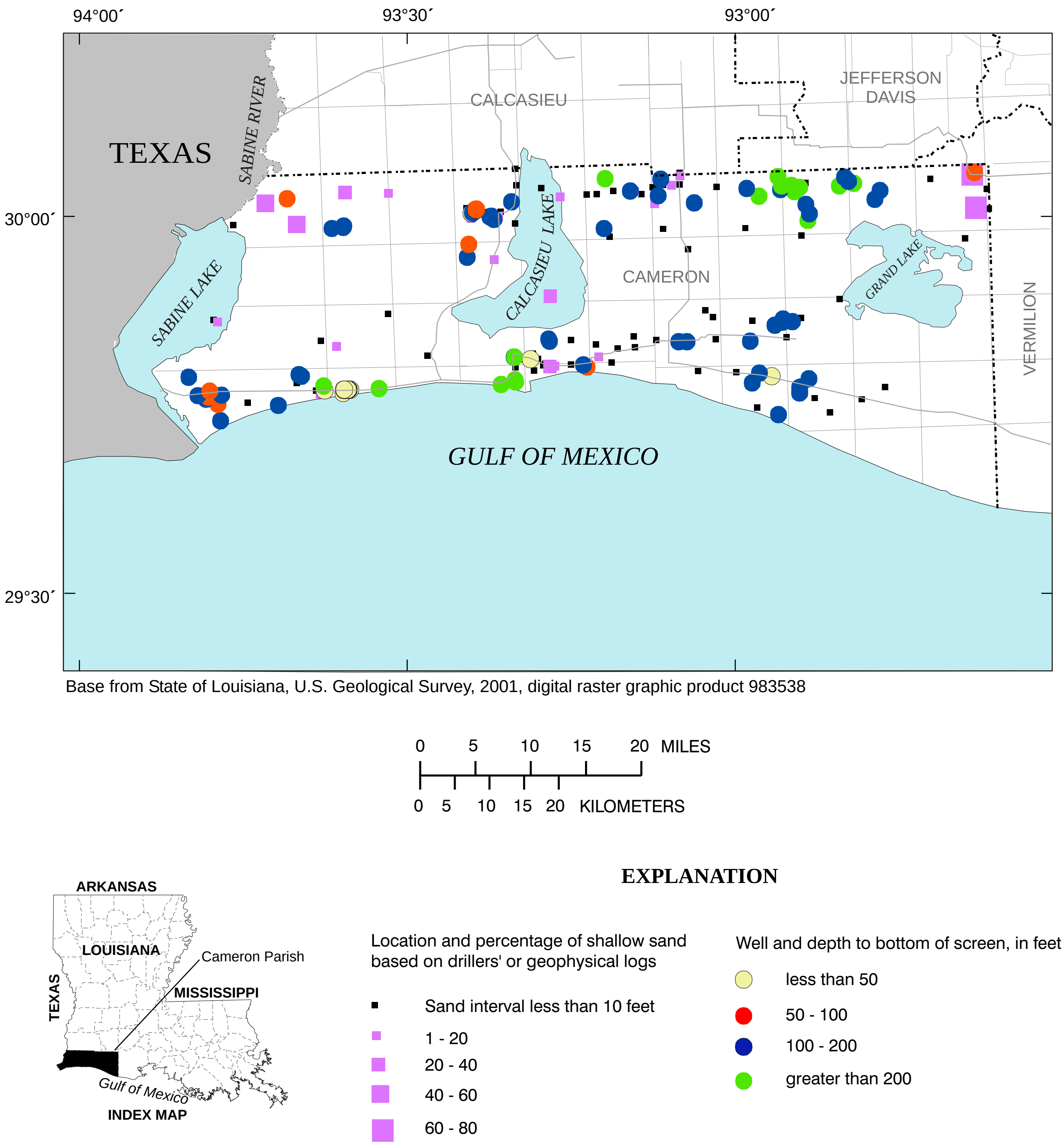


Figure 9. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Cameron Parish, southwestern Louisiana.

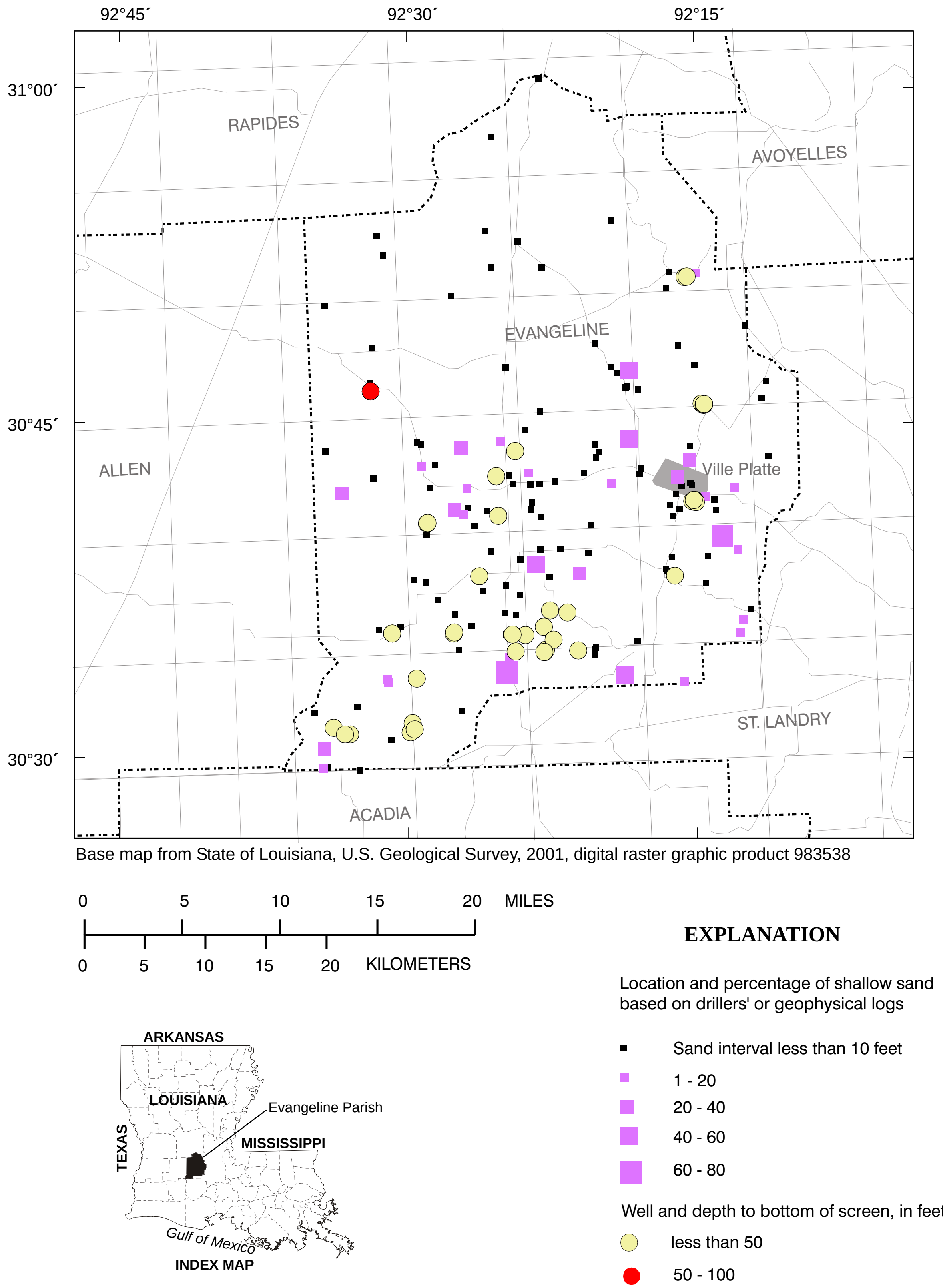


Figure 10. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Evangeline Parish, southwestern Louisiana.

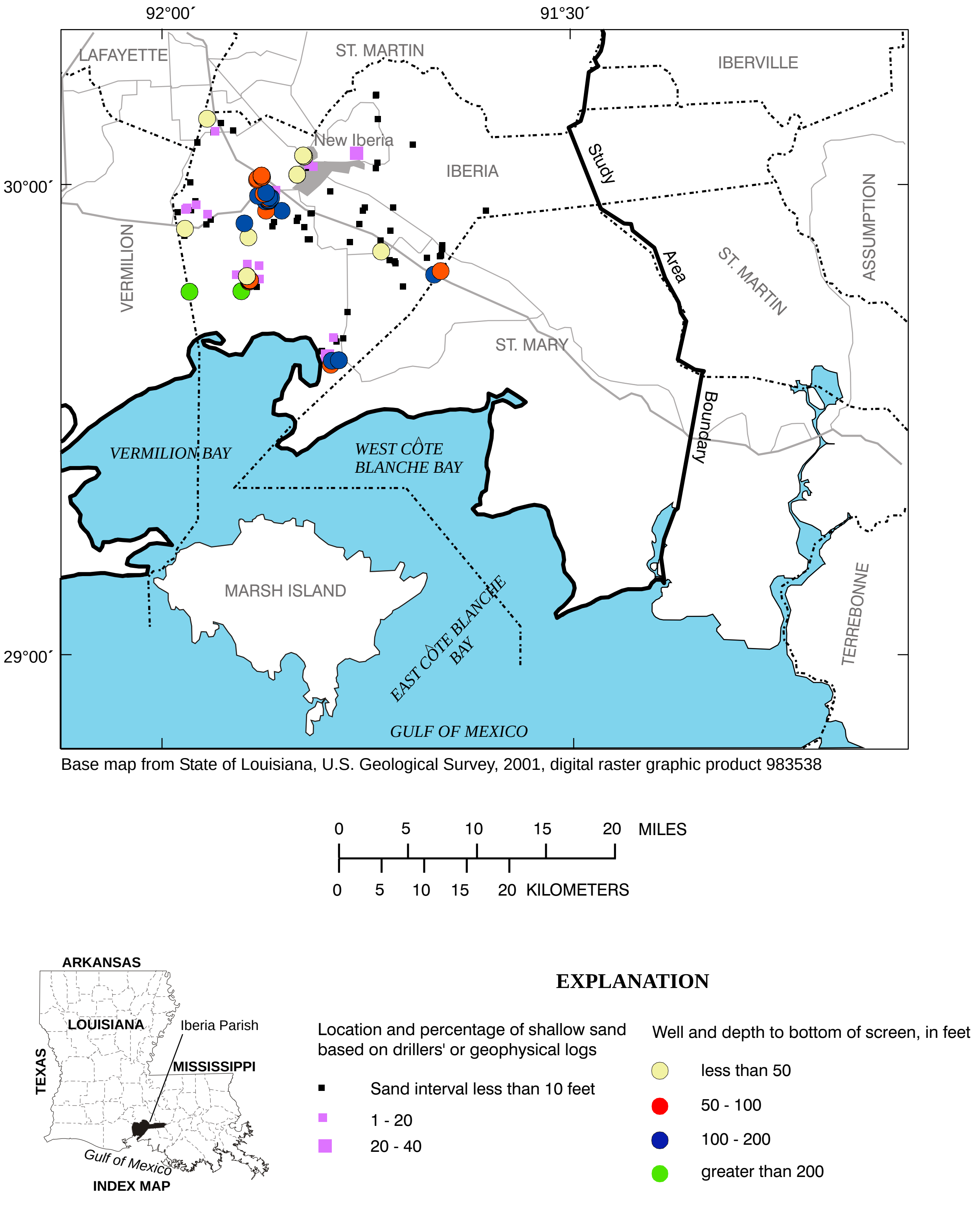


Figure 11. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Iberia Parish, southwestern Louisiana.

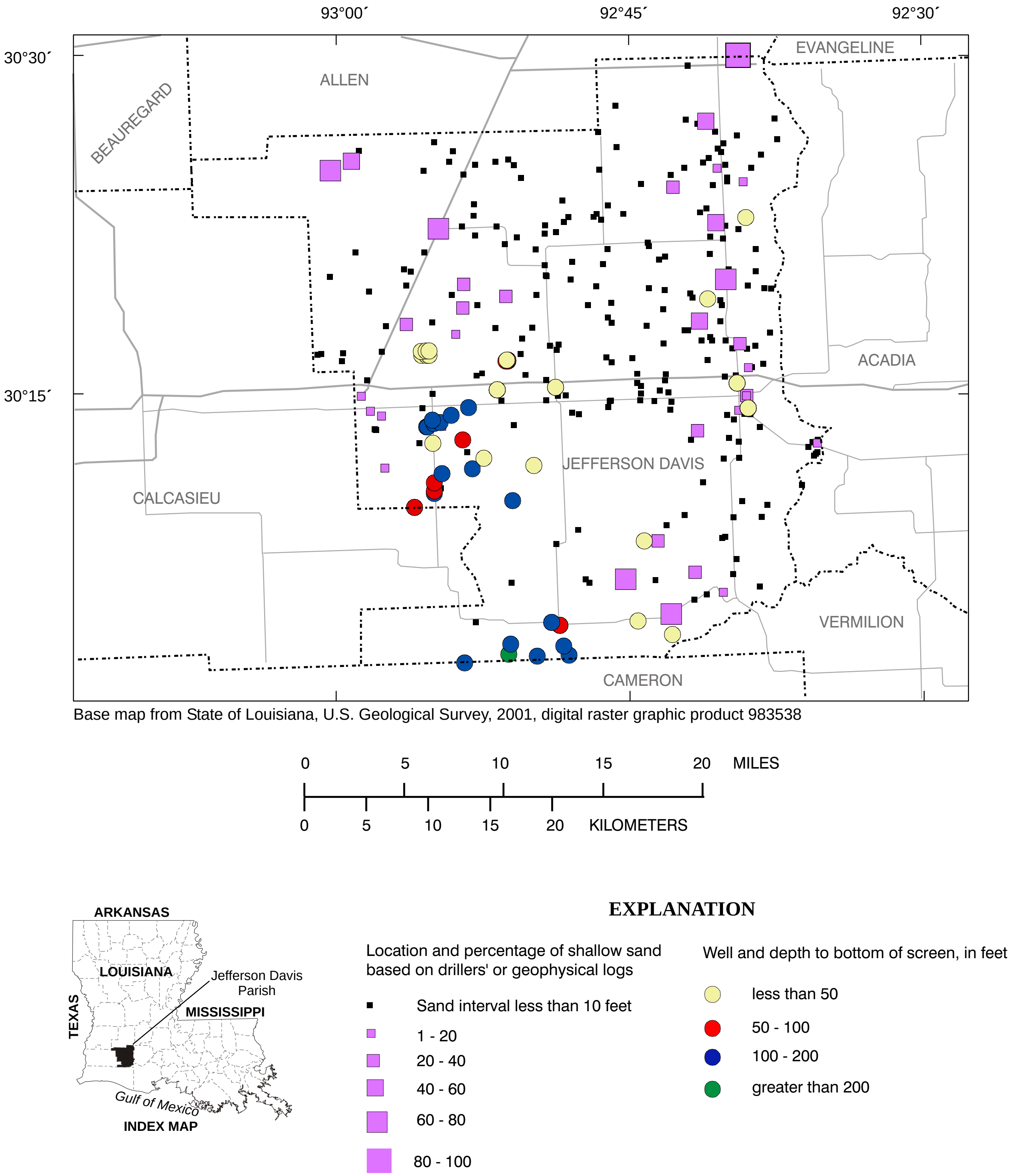


Figure 12. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Jefferson Davis Parish, southwestern Louisiana.

depths range from 11 to 210 ft, with a mean depth of 66 ft (table 1). Well logs showing shallow sands generally are located along the eastern and southern boundaries and in the northwestern corner of the parish. Shallow sands were notably absent on logs from the central and north-central parts of the parish.

In Lafayette Parish, wells screened in shallow sands are at depths less than 50 ft in the eastern and central parts of the parish, but are mostly screened between 50 and 100 ft in the western part of the parish (fig. 13). Two wells show a screen depth in the 100 to 200 ft range. Well screen depths range from 5 to 116 ft, with a mean depth of 36 ft (table 1). Well logs were evenly distributed throughout the parish, but generally only showed shallow sands in the southeastern and western parts of the parish.

In St. Landry Parish, wells screened in shallow sands are generally located in the southwestern part of the parish. Well screens for the shallow wells vary in depth from less than 50 ft to 200 ft (fig. 14). Well screen depths range from 12 to 110 ft, with a mean depth of 27 ft (table 1). Well logs are evenly distributed throughout the parish, but generally shallow sands only are evident in the western half of the parish. The logs indicate that percentage of the confining unit composed of shallow sands is highest in St. Landry Parish and averages about 36 percent (table 1).

In St. Mary Parish, wells screened in shallow sands are located in that part of the parish which is in the study area, the western half. Well screens for the shallow wells vary in depth from less than 50 ft to greater than 200 ft (fig. 15). Well screen depths range from less than 10 to 326 ft, with a mean depth of 183 ft (table 1). Little fresh ground water is available in the southern parts of St. Mary Parish (Harder and others, 1967, pl. 5), so rural domestic water-supply and petroleum rig-supply wells are generally located in the western half of the parish. Well logs that showed shallow sands generally are located in the northwestern part of the parish.

In Vermilion Parish, wells screened in shallow sands are mostly located in the eastern part of the parish. Well screens for the shallow wells vary in depth from less than 50 ft to greater than 200 ft (fig. 16). Well screen depths range from 12 to 350 ft, with a mean depth of 98 ft (table 1). Because much of western and southern Vermilion Parish is marshy and uninhabited, most wells and well logs are located in the northeastern part of the parish (fig. 16). Many of the 61 logs indicate that shallow sands compose more than 60 percent of the surficial confining unit in this area.

SUMMARY AND CONCLUSIONS

Southwestern Louisiana is located within the Gulf Coastal Plain physiographic province. The area is underlain by thick multilayered sequences of unconsolidated sedimentary deposits that alternate between gravel, sand, silt, and clay and have a predominant dip to the south. The sand and gravel deposits form productive aquifer units and they, along with adjoining clay and silt deposits, are designated as the Chicot aquifer system. The Chicot aquifer system underlies an area of approximately 9,000 square miles in southwestern Louisiana and is the principal source of fresh ground water in the region. The dense surficial clays that confine the upper sands of the Chicot aquifer system are known as the Chicot aquifer system surficial confining unit.

Although the confining unit may be relatively uniform in composition across large areas, interbedded sands of varied areal extent and thickness are present within the confining unit. These sands are collectively known as the shallow sands of the Chicot aquifer system. The shallow sands occur irregularly throughout the confining unit and may provide sufficient water for small-diameter wells that supply water for domestic, irrigation, or petroleum rig-supply purposes.

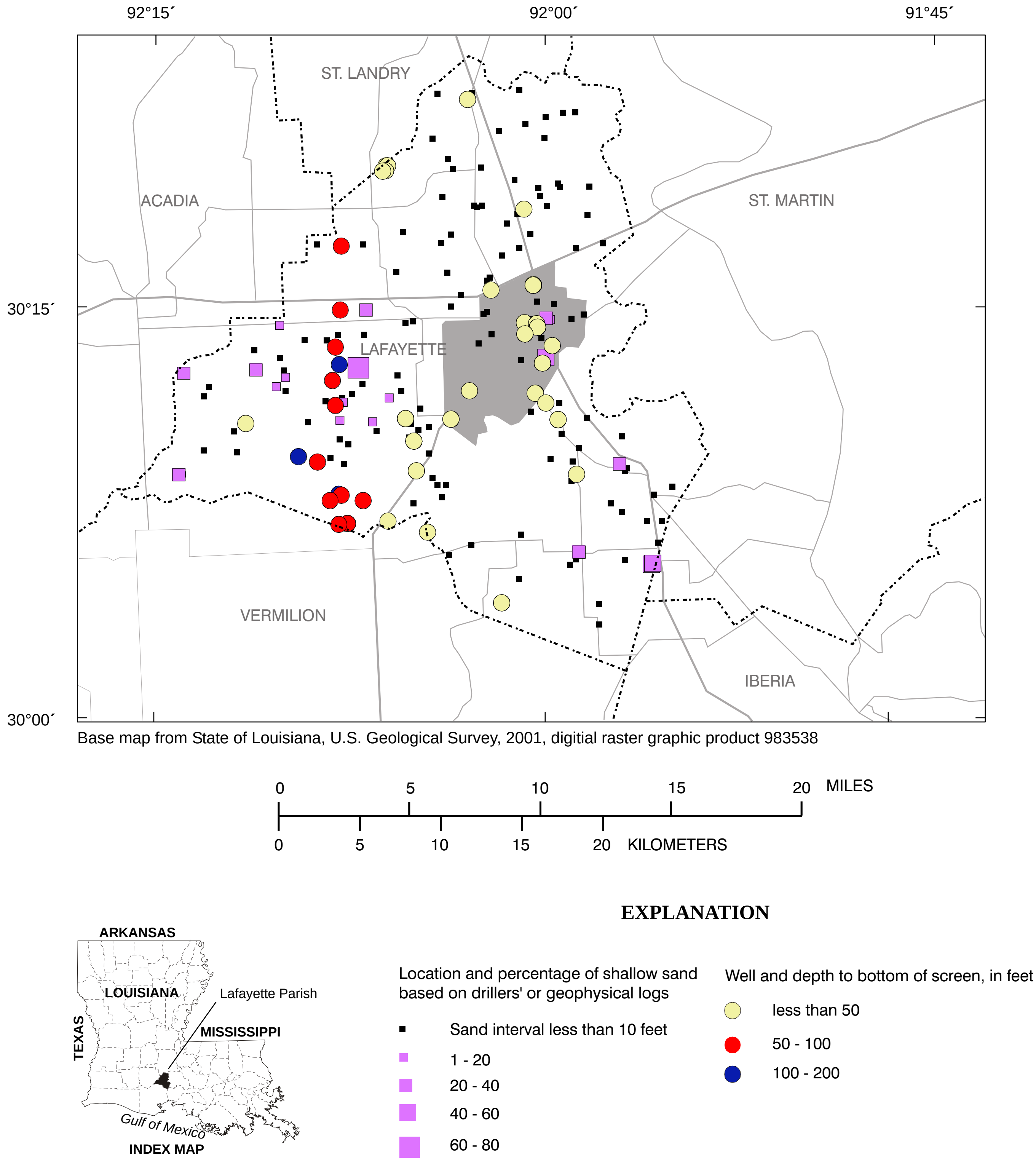


Figure 13. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Lafayette Parish, southwestern Louisiana.

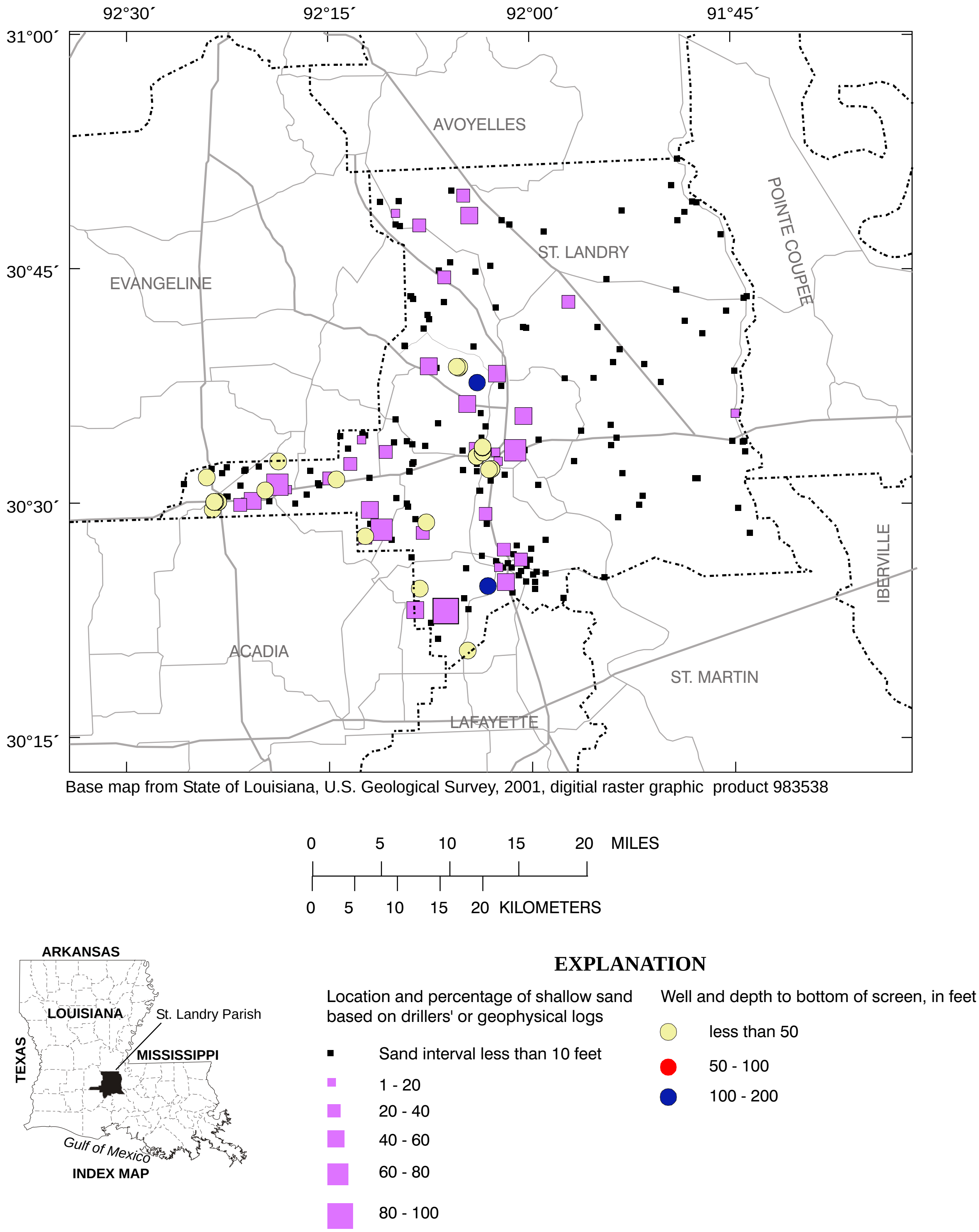


Figure 14. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in St. Landry Parish, southwestern Louisiana.

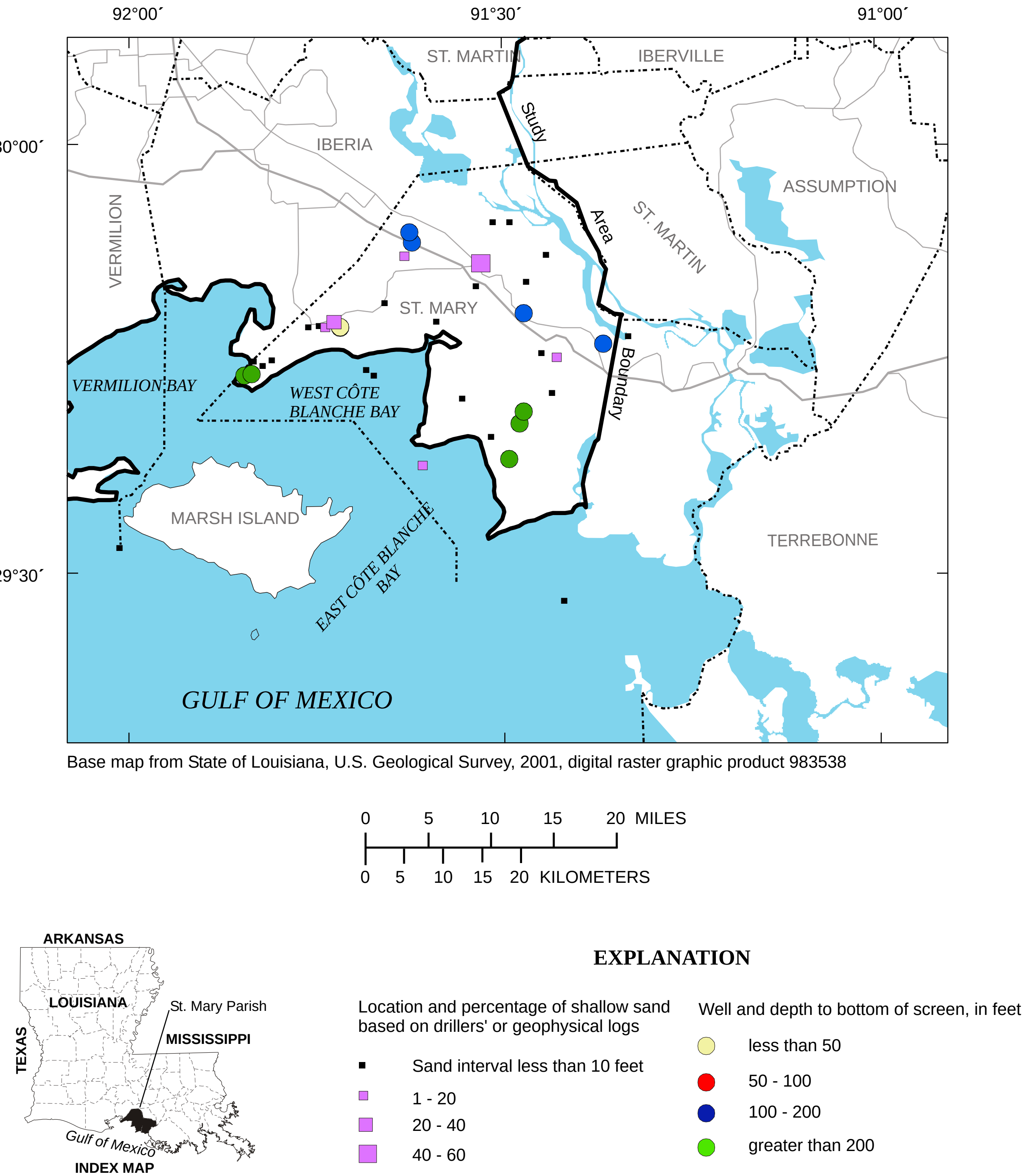
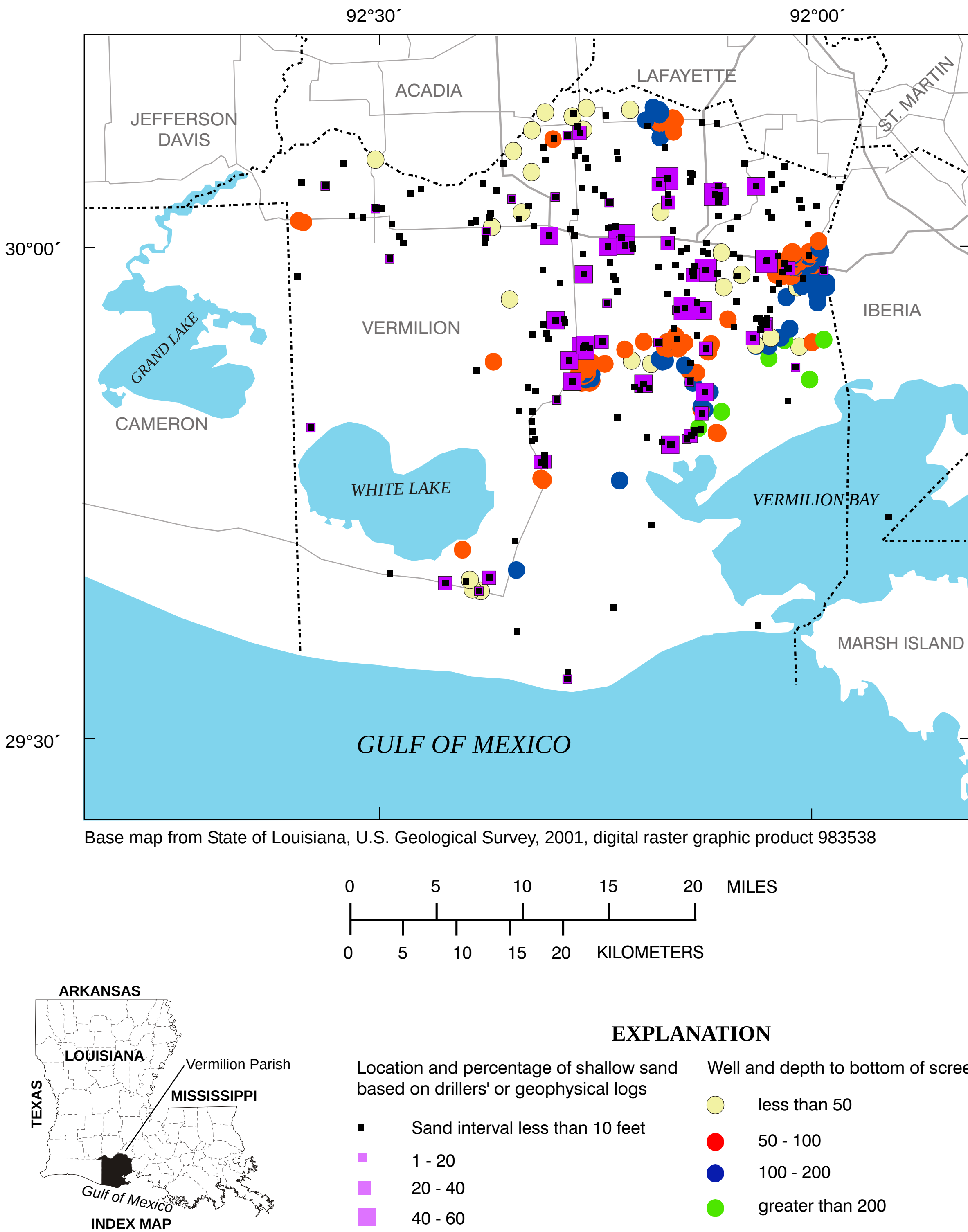


Figure 15. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in St. Mary Parish, southwestern Louisiana.



EXPLANATION

Location and percentage of shallow sand based on drillers' or geophysical logs

- Sand interval less than 10 feet
- 1 - 20
- 20 - 40
- 40 - 60
- 60 - 80
- 80 - 100

Well and depth to bottom of screen, in feet

- less than 50
- 50 - 100
- 100 - 200
- greater than 200

Figure 16. Location of bottom of well screens and well logs with percentage of shallow sand within the Chicot aquifer system surficial confining unit in Vermilion Parish, southwestern Louisiana.

Drillers' logs, geophysical logs, and information from shallow wells were used to define the thickness of the confining unit and locate areas of shallow sands. The thickness of the surficial confining unit generally increases from north to south. In southern Vernon and Rapides Parishes, where the Chicot aquifer system crops out, the confining unit typically is less than 40 feet thick. The thickness of the confining unit generally increases southward, and generally ranges in thickness from 160 to 400 feet in coastal parishes with a maximum thickness of about 520 feet in Vermilion and St. Mary Parishes. Because the quality of the drillers' logs varies, an analytical methodology was developed to identify the best drillers' logs and integrate higher-quality information from other sources, such as published reports.

The presence of shallow sands was documented in 12 of the 15 parishes in the study area. Well-log data from Vernon, Rapides, and St. Martin Parishes showed no shallow sands greater than 10 ft in thickness. Location and depth information of water-supply wells screened in shallow sands within the confining unit complemented the well log information with respect to the areal distribution of shallow sands. The screen depths ranged from 4 to 350 ft, and the maximum mean screen depth in a parish was 183 ft. Well location and depth to bottom of screen of the wells were mapped for the 12 parishes where shallow sands are present. The location of well logs with greater than a 10 ft sand interval and the percent shallow sand within the confining unit also were mapped for the 12 parishes in the study area. The locations of wells screened within the surficial confining unit and drillers' or geophysical logs showing shallow sands greater than 10 feet thick are mapped for 12 of the 15 parishes in the study area. The percentage of shallow-sand thickness in the confining unit is indicated for each log. Well-screen depths of 1,579 shallow wells used for domestic, irrigation, or petroleum rig-supply purposes were assumed to indicate the presence of productive shallow sands within the confining unit; however, only about 19 percent of the 2,098 logs analyzed indicate that shallow sands are present. The logs also indicate that the percentage of shallow-sand thickness in the confining unit can vary greatly across very short distances.

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SMOOT, 1988

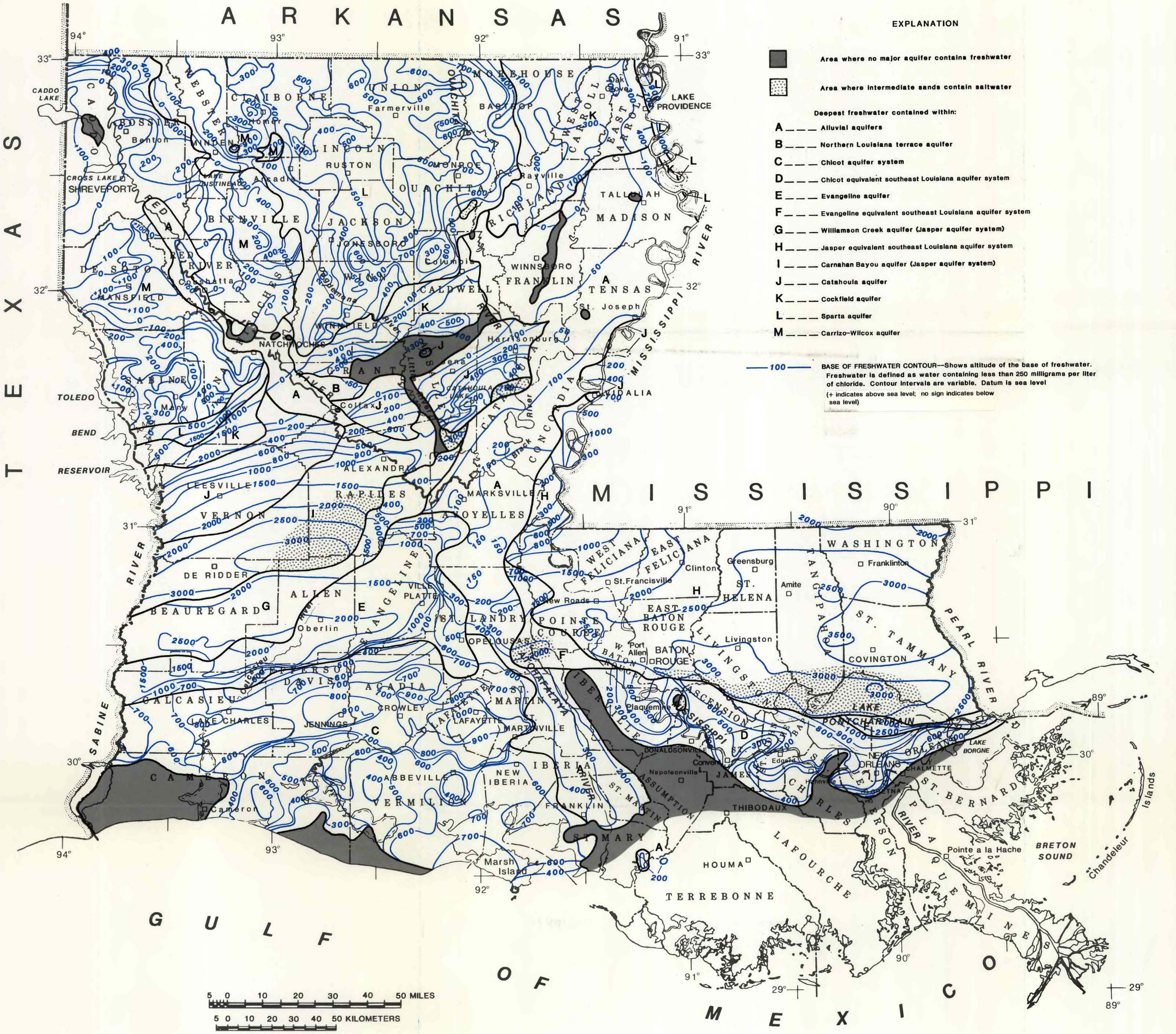
LOUISIANA HYDRAULIC ATLAS MAP NO. 3

ALTITUDE OF THE BASE OF THE FRESHWATER IN LOUISIANA

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
LOUISIANA DEPARTMENT OF TRANSPORTATION AND DEVELOPMENT

WATER-RESOURCES INVESTIGATIONS
REPORT 86-4314



EXPLANATION

Area where no major aquifer contains freshwater

Area where intermediate sands contain saltwater

Deepest freshwater contained within:

A ____ Alluvial aquifers
B ____ Northern Louisiana terrace aquifer
C ____ Chicot aquifer system
D ____ Chicot equivalent southeast Louisiana aquifer system
E ____ Evangeline aquifer
F ____ Evangeline equivalent southeast Louisiana aquifer system
G ____ Williamson Creek aquifer (Jasper aquifer system)
H ____ Jasper equivalent southeast Louisiana aquifer system
I ____ Carnahan Bayou aquifer (Jasper aquifer system)
J ____ Catahoula aquifer
K ____ Cockfield aquifer
L ____ Sparta aquifer
M ____ Carrizo-Wilcox aquifer

—100— BASE OF FRESHWATER CONTOUR--Shows altitude of the base of freshwater. Freshwater is defined as water containing less than 250 milligrams per liter of chloride. Contour intervals are variable. Datum is sea level

(+ indicates above sea level; no sign indicates below sea level)

INTRODUCTION

A map showing the base of fresh ground water in Louisiana was first prepared by Rollo in 1960. With subsequent investigations and the collection of additional data, the need to update Rollo's map became apparent. In 1984 the U.S. Geological Survey began a cooperative investigation with the Louisiana Department of Transportation and Development to refine knowledge of the base of fresh ground water in Louisiana.

This map defines the altitude of the base of freshwater in Louisiana, shows areas where no major aquifer contains freshwater, and also shows areas where sands that contain saltwater in intermediate zones between deep zones of freshwater and land surface are found.

Freshwater, for this report, is defined as water that contains a chloride concentration of less than 250 milligrams per liter. Water that contains this concentration of chloride meets the U.S. Environmental Protection Agency secondary drinking water standards (U.S. Environmental Protection Agency, 1979).

Data for this map were obtained from recently published maps by interpretation of electric-resistivity logs of water and oil wells. (For method of calculation of water quality from electrical logs, see Turcan, 1966.) Map data from some recent studies were modified for this map, and map data from parts of the base-of-freshwater maps by Harder and others (1967), Whiteman (1972), Rogers (1981), and Ryals (1982) were used unmodified. Data from approximately 2,000 electric-resistivity logs were used for this project. More than 1,000 of these logs were from test water wells drilled by the Louisiana Department of Transportation and Development and the U.S. Geological Survey. Water-quality analyses from many of the test water wells confirmed the interpretation of the electrical logs. The majority of the electrical logs used for this map were made during the past 20 years. However, a few of the logs used were made over 40 years ago.

The major aquifer that contains the deepest freshwater of each area is contoured individually. As most major aquifers are separated from each other by thick clay intervals, the base of freshwater may change abruptly. For example, in northern Vernon Parish, where the base of freshwater changes from within the Cockfield aquifer to within the Catahoula aquifer, the base of freshwater changes approximately 1,500 ft (feet) within 1 mi (mile). South of Baton Rouge, the base of freshwater changes more than 2,000 ft in less than 5 mi. Each aquifer is identified on this map, accompanied by contour lines showing the altitude of the base of freshwater. These areas do not represent the total areal extent of the respective aquifer, but only the area where the deepest freshwater occurs in that respective aquifer.

The contours for this map have variable intervals but generally are on 100-foot intervals above or below sea level to a depth of 1,000 ft. For depths 1,000 ft below sea level, the contour interval is 500 ft. To show detail in the area where the base of freshwater is within the shallow alluvial aquifers in northern Louisiana, a contour interval of 50 ft is used. In gray areas, none of the major aquifers contains freshwater. To obtain the maximum depths of freshwater below land surface where the altitude of freshwater occurrence is above sea level, subtract this value from land surface elevation. Where the occurrence of the altitude of freshwater is below sea level, add the value to the land-surface elevation.

BASE OF FRESHWATER

The depth to the base of freshwater is highly variable. Freshwater can be found as deep as 3,500 ft below sea level in southeastern Louisiana, but fresh ground water cannot be found at any depth in a few parts of the State.

Some areas that recently contained freshwater may now contain saltwater. For example, pumping wells near the downdip limit of freshwater within a sand causes saltwater to move laterally toward the center of pumping. If the wells are close to the saltwater front, they may yield water of increasing salinity. Pumping from the upper part of a sand in the transition zone will cause saltwater to move vertically toward the well, and saltwater may eventually contaminate the well.

In some areas, the only fresh ground water occurs in shallow aquifers. Locally these shallow aquifers have been contaminated by saltwater introduced during the drilling of oil and gas wells by upward movement from deep saline aquifers through open boreholes, and by oil and gas related evaporation ponds. Once the contaminated saltwater moves into the aquifer, it flows very slowly downdip toward natural discharge areas or toward pumping centers. Thus the areas of contaminated freshwater may change with time.

In places, saltwater-bearing sands may occur in intermediate zones between the deep zones and shallow zones of freshwater. The areas where sands contain saltwater in intermediate zones are shown on the map by dot patterns. Within the areas mapped as having intermediate zones of saltwater, most of the interval may contain saltwater, and an isolated, deep, freshwater-bearing sand may be the basis for contouring. For example, the only freshwater in a test well in St. John the Baptist Parish is in two intervals, 545 to 595 ft and 2,830 to 3,045 ft. All other intervening sands contain saltwater. In other areas, the intermediate saltwater may occur in only one sand above the lowermost freshwater-bearing sand. For example, the only intermediate saltwater-bearing sand in an oil-test well in Rapides Parish is from 920 to 1,080 ft. All other sand beds between land surface and a depth of 2,090 ft contain freshwater.

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For additional information write to:

District Chief
U.S. Geological Survey
P.O. Box 66492
Baton Rouge, Louisiana 70896
Telephone: (504) 389-0281

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LOUISIANA HYDROLOGIC ATLAS MAP NO. 3 : ALTITUDE OF THE BASE OF FRESHWATER IN LOUISIANA

By
Charles W. Smoot

1988

STOLPER, K., 1994

CALCULATE A MORE ACCURATE WATER SALINITY BY VISUALLY ELIMINATING "M"

Calculate a More Accurate Water Saturation by Visually Estimating "m"

by Kathy Stolper
Stolper Geologic, Inc.

Water saturation calculations derived from wireline log responses have historically assumed "m" = 2 when "m" (the cementation exponent) is unknown. This practice can lead to erroneously high values for water saturation, and possibly by-passed pay, since there are many instances where "m" is less than 2.

The Archie "m" can be measured in the laboratory, but this is an expensive ($300-$500 per sample) and time-consuming process. Also, rotary core plugs are required for the analysis. Measurement cannot be obtained with cuttings or sidewall core samples. A quicker and less expensive alternative (and the only alternative if rotary core plugs are unavailable) is to estimate "m" by comparing your samples to rocks with known "m" values. Rather than assuming "m" = 2, a more accurate estimate can be made to more accurately calculate water saturation.

Visual evaluation of cuttings, sidewall core, and/or whole core using a binocular microscope at 20X to 50X magnification will allow you to describe the many features of a rock which affect Archie "m". Once these features have been described, an accurate estimate of "m" can be made.

Pattern recognition skills are useful for visually estimating Archie "m" since it is based on the familiarization of rock comparators which have measured "m" values. The comparators referred to here can be the ones supplied to members of the Shell Rock Catalog, or similar ones which companies make for their private use. Once a frame of reference has been established for rocks with measured "m", estimates can be made for rocks with unknown "m". An accurate visual estimate of Archie "m" ultimately requires practice and patience. The best way to acquire this skill is through the use of rock comparators.

The cementation exponent "m" is related to the pore geometry of the rock; therefore, it is extremely important that you view a dry, freshly broken surface for this examination.

The effects on "m" can be said to be associated with the concept of order versus disorder. That is, the more orderly the pore geometry of a rock, the lower the value of "m"; conversely, the more disorderly the pore geometry, the higher the "m" value.

The cementation exponent can vary from 1.2 to 2.2 for sandstones, and can be as high as 3.1 for carbonates. The following is a list of factors which can influence "m" (if the porosity remains unchanged), along with the reasons for their impact on "m":

1. An increase in grain sorting decreases "m" since the pore geometry becomes more orderly.

2. An increase in cement increases "m" because the pore geometry becomes more disorderly.

3. An increase in compaction increases "m" because pore throats are cut off, thus isolating pores.

4. An increase in "patchy" cement increases "m" due to the breaks in net electrical continuity.

5. A decrease in grain size increases "m" because the surface area to grain volume increases.

6. Bimodality increases "m" because the pore geometry becomes more disorderly.

7. An increase in the amount of interconnected vugs increases "m" because the pore geometry becomes more disorderly.

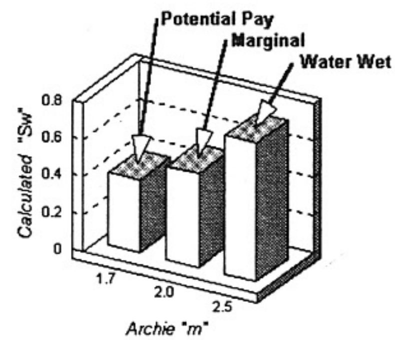
8. An increase in the amount of clay increases "m" because the surface area to grain volume increases. Some clay types will have more of an effect than others because of the variation in cation exchange capacities (CEC). The greater the CEC, the greater the conductivity, the lesser the effect on "m". The commonly encountered clay minerals in order of increasing CEC and decreasing effect on the value of "m" are: kaolinite with CEC of 3 to 15, chlorite and illite with CEC of 10 to 40, and smectite with CEC of 80 to 150.

9. For carbonates, "m" is affected by particle size, interparticle porosity, and vuggy porosity (isolated and interconnected).

All of these contributing factors are visible features of the rock and can be used to visually estimate Archie "m". Cuttings are a readily available source from which an accurate and inexpensive estimate of "m" can be made. The more accurate the "m", the more accurate the water saturation calculation, which ultimately leads to a reduced danger of bypassing pay.

For more information contact the author at 16688 W 73rd Drive
Arvada, CO 80007
303-674-3100
www.stolpergeologic.com

ASSUMING "m" = 2 CAN LEAD TO POOR COMPLETION DECISIONS



This graph shows how varying the value of "m" affects calculated water saturation when all else remains constant. A more accurate "m" is quickly and inexpensively estimated from visual rock analysis. This greatly increases your chances for success.

USGS, 2017

WATER RESOURCES OF CALCASIEU PARISH, LOUISIANA

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LOUISIANA DEPARTMENT OF TRANSPORTATION & DEVELOPMENT

Prepared in cooperation with the Louisiana Department of Transportation and Development

Water Resources of Calcasieu Parish, Louisiana

Introduction

Information concerning the availability, use, and quality of water in Calcasieu Parish, Louisiana (fig. 1), is critical for proper water-resource management. The purpose of this fact sheet is to present information that can be used by water managers, parish residents, and others for stewardship of this vital resource. Information on the availability, past and current use, use trends, and water quality from groundwater and surface-water sources in the parish is presented. Previously published reports (see References Cited section) and data stored in the U.S. Geological Survey's National Water Information System (http://dx.doi.org/10.5066/F7P55KJN) are the primary sources of the information presented here.

In 2010, about 223.7 million gallons per day (Mgal/d) of water were withdrawn in Calcasieu Parish, including about 136.7 Mgal/d from surface-water sources and 87.0 Mgal/d from groundwater sources.[1] Withdrawals for industrial use accounted for the majority (156.5 Mgal/d) of total water withdrawn (tables 1–2). Other categories of use included public supply, power generation, rural domestic, livestock, rice irrigation, general irrigation, and aquaculture. Water-use data collected at 5-year intervals from 1960 to 2010 (fig. 2) indicated that water withdrawals peaked in 1970 at about 1,020 Mgal/d. The generally downward trend in water withdrawals from 1960 to 2010 is largely attributable to reductions in withdrawals for industrial use and rice irrigation.

[1]Water-withdrawal data are based on estimated or reported site-specific data and aggregated data, which are distributed to sources. For a full description of water-use estimate methodology, see "Data Collection" in Sargent (2011). Tabulation of numbers in text and tables may result in different totals because of rounding; nonrounded numbers are used for calculation of totals.

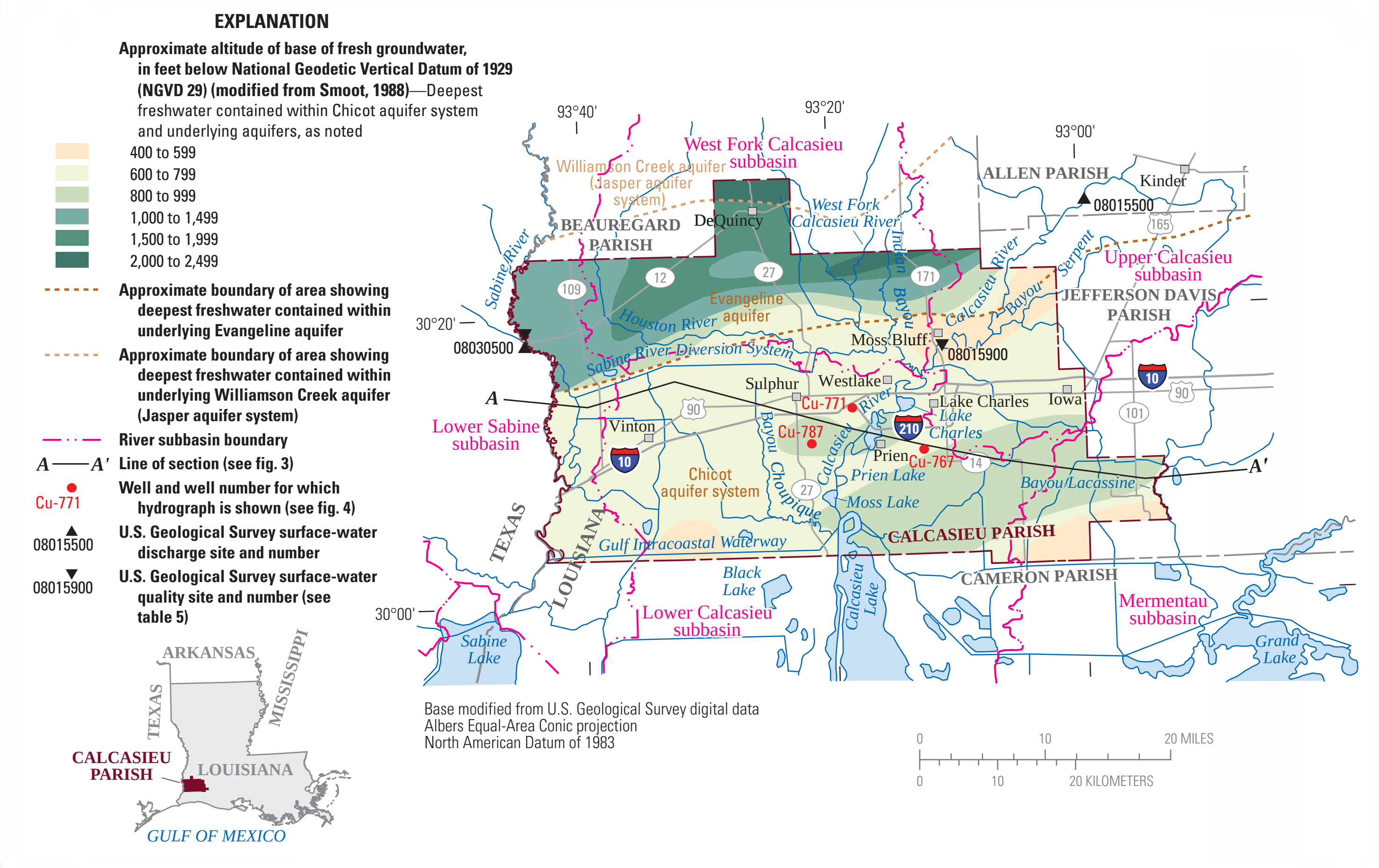

Figure 1. Location of study area, Calcasieu Parish, Louisiana.

Table 1. Groundwater withdrawals, in million gallons per day, by source and use category in Calcasieu Parish, Louisiana, 2010 (B.P. Sargent, U.S. Geological Survey, written commun., 2015).

[<, less than]

Use category	Chicot aquifer system					Evangeline aquifer	Total by use
	"200-foot" and upper sand	"500-foot" sand	"700-foot" and lower sand	Undifferentiated sand	Shallow sand		
Public supply	1.19	21.62	2.10	0.04	0.00	0.79	25.73
Industrial	1.16	39.35	<0.01	0.72	0.00	0.00	41.23
Power generation	0.00	6.46	0.00	0.00	0.00	0.00	6.46
Rural domestic	1.56	0.53	0.00	0.02	0.11	0.00	2.23
Livestock	0.10	0.03	0.01	0.04	0.01	0.00	0.20
Rice irrigation	3.71	2.29	0.63	0.95	0.32	0.00	7.90
General irrigation	0.18	0.11	0.02	0.00	0.03	0.00	0.34
Aquaculture	0.58	0.58	0.58	0.00	1.16	0.00	2.90
Total by source	**8.49**	**70.97**	**3.35**	**1.77**	**1.63**	**0.79**	**87.00**

Table 2. Surface-water withdrawals, in million gallons per day, by source and use category in Calcasieu Parish, Louisiana, 2010 (B.P. Sargent, U.S. Geological Survey, written commun., 2015).

Use category	Calcasieu River	Gulf Intracoastal Waterway	Sabine River Diversion System	Miscellaneous streams	Total by use
Public supply	0.00	0.00	0.50	0.00	0.50
Industrial	76.17	0.01	39.12	0.00	115.30
Power generation	0.05	0.00	14.46	0.00	14.51
Livestock	0.00	0.00	0.00	0.30	0.30
Rice irrigation	0.00	0.00	0.00	3.77	3.77
Aquaculture	0.00	0.00	0.00	2.34	2.34
Total by source	**76.22**	**0.01**	**54.07**	**6.42**	**136.72**

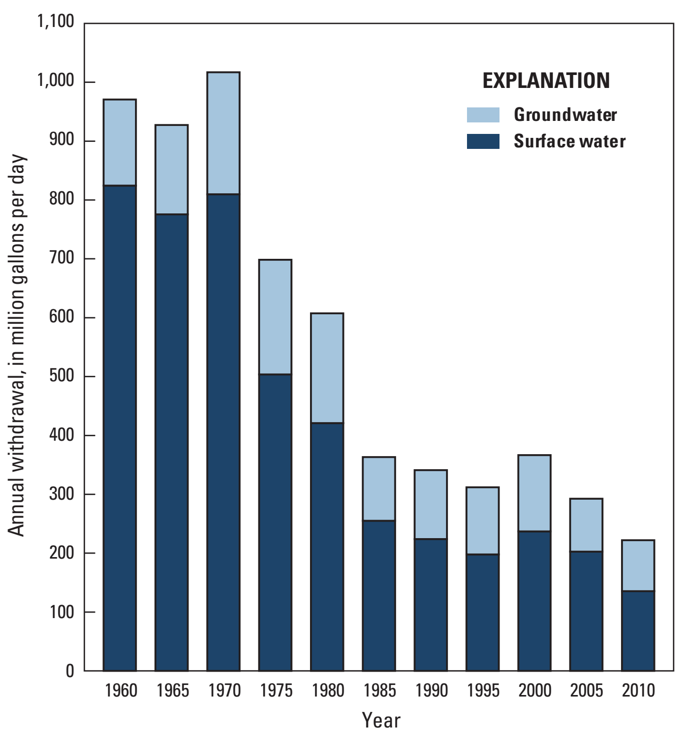

Figure 2. Water withdrawals in Calcasieu Parish, Louisiana, 1960–2010 (Sargent, 2011).

Groundwater Resources

Fresh groundwater (water with a chloride concentration of 250 milligrams per liter [mg/L] or less) is available in Calcasieu Parish in several different aquifers to varying depths, depending on location. The base of freshwater in Calcasieu Parish ranges from about 400 feet (ft) below the National Geodetic Vertical Datum of 1929 (NGVD 29) to almost 2,500 ft below NGVD 29. The deepest freshwater is north of DeQuincy within the Williamson Creek aquifer. In the rest of the roughly northern quarter of the parish, the base is present at depths from about 700 to 2,000 ft or more below NGVD 29 within the Evangeline aquifer. In the southern three-fourths of the parish, the base of freshwater ranges in depth from about 500 to 800 ft below NGVD 29 and is within the Chicot aquifer system (fig. 1; Smoot, 1988).

The Chicot Aquifer System

The Chicot aquifer system is an important regional aquifer system underlying most of southwestern Louisiana. The aquifer system crops out and receives recharge in parishes to the north and northeast of Calcasieu Parish where the aquifer system is largely composed of one, major, undifferentiated sand. The undifferentiated sand thickens and deepens to the south and, near the northern border of Calcasieu Parish (fig. 1), becomes subdivided into a complex series of sand layers by clay confining layers. West of about the longitude of the town of Iowa (fig. 1), these divisions consist of the "200-foot," "500-foot," and "700-foot" sands of the Lake Charles area (fig. 3). East of this longitude, these divisions consist of the Chicot aquifer upper and lower sands, which are hydraulically connected to the "200-foot" and "700-foot" sands, respectively (fig. 3).

A surficial confining layer of clay restricts infiltration of precipitation into the groundwater system throughout the parish. The surficial confining layer thickness ranges from 40 ft in small areas in northwestern and northeastern Calcasieu Parish to 280 ft in the south-central part of the parish (Sargent, 2004). Within the surficial confining clay are scattered sand streaks, sand lenses, and sand layers collectively named the "shallow sand unit of the Chicot aquifer system."

The primary aquifers in the parish are the "200-foot," "500-foot," and "700-foot" sands (table 1), and these aquifers share similar characteristics but are present at varying depths. The "200-foot" sand generally grades from fine to medium sand at the top to a coarse sand or gravel at the base (Harder, 1960). The top of the sand is present at depths of zero to 50 ft above NGVD 29 near the northeastern corner of the parish and greater than 300 ft below NGVD 29 in the southwestern corner of the parish (Harder, 1960). The "500-foot" sand generally grades from fine sand at the top to coarse sand and gravel near the base (Harder, 1960). The top of the "500-foot" sand is present at less than 400 ft below NGVD 29 in northern areas of the parish and reaches over 600 ft below NGVD 29 in the southeastern corner of the parish (Nyman, 1984). The base of the "500-foot" sand ranges from greater than 400 ft below NGVD 29 in the northern part of the parish to greater than 800 ft below NGVD 29 in the southeastern corner of the parish (Nyman, 1989). The "700-foot" sand is generally tan to grayish and grades from fine sand at the top to coarse sand at the base (Harder, 1960). The top of the "700-foot" sand is present at depths of less than 400 ft below NGVD 29 in the northern part of the parish and reaches depths exceeding 800 ft below NGVD 29 in the southeastern corner of the parish. The base of the lower sand and "700-foot" sand ranges from greater than 400 ft in the northern tip of the parish to greater than 1,000 ft in the southeastern corner of the parish (Nyman, 1989). In 2015, more than 4900 active wells were screened in Chicot aquifer system in Calcasieu Parish, with most of them being screened in these three primary aquifers from depths of 13 to 849 ft, with yields of up to 5,471 gallons per minute (Louisiana Department of Natural Resources, written commun., 2015) (table 3).

Water levels in wells in all three sands in Calcasieu Parish showed similar spatial and temporal patterns. In 2011–12, water levels in wells screened in the "200-foot," "500-foot," and "700-foot" sands in Calcasieu Parish ranged from highs of approximately 7.6 ft above, 2.4 ft below, and 14.1 ft below NGVD 29, respectively, to lows of 49.9 ft below, 79.6 ft below, and 69.6 ft below NGVD 29, respectively (U.S. Geological Survey, 2016a). Spatially, water levels in wells in all three sands were lowest near the Calcasieu River in the Lake Charles metropolitan area, corresponding well to the documented movement of groundwater toward this area (Nyman, 1984; Lovelace, 1998). Water levels in wells have varied in similar ways over time and have risen in general by as much as 20 ft since the 1970s (fig. 4), because of decreased pumping.

Groundwater Quality

Freshwater samples collected from 111 wells screened in the "200-foot" sand, 239 wells screened in the "500-foot" sand, and 63 wells screened in the "700-foot" sand had median hardness values in the moderately hard range.[2] Over 90 percent of samples in each aquifer did not exceed the U.S. Environmental Protection Agency's Secondary Maximum Contaminant Levels (SMCLs)[3] for pH. Over 80 percent of samples in each aquifer did not exceed the SMCL for dissolved-solids concentrations. Median values for iron concentrations were below the SMCL in the "200-foot" sand and greatly exceeded the SMCL in the "500-foot" and "700-foot" sands (table 4).

Saltwater (water with a chloride concentration greater than 250 mg/L) is present in both local and widespread areas within the Chicot aquifer system in Calcasieu Parish. At the base of the "200-foot" sand and in the upper sand, saltwater is present along most of the southern parish boundary, in the southeastern corner of the parish, and in a localized area near Iowa. At the base of the

[2]Hardness ranges, expressed as milligrams per liter of calcium carbonate, are as follows: 0–60, soft; 61–120, moderately hard; 121–180, hard; greater than 180, very hard (Hem, 1985).

[3]The SMCLs are nonenforceable Federal guidelines regarding cosmetic effects (such as tooth or skin discoloration) or aesthetic effects (such as taste, odor, or color) of drinking water. At high concentrations or values, health implications as well as aesthetic degradation might exist. SMCLs were established as guidelines for the States by the U.S. Environmental Protection Agency (2016).

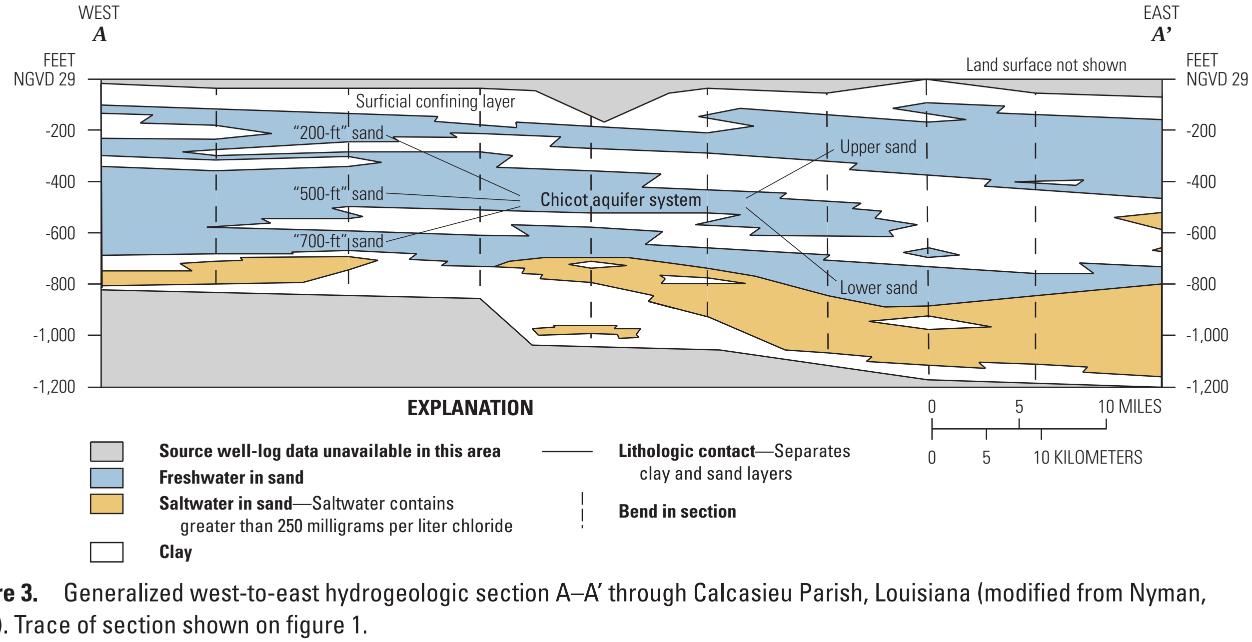

Figure 3. Generalized west-to-east hydrogeologic section A–A' through Calcasieu Parish, Louisiana (modified from Nyman, 1984). Trace of section shown on figure 1.

Table 3. Active registered wells in the Chicot aquifer system in Calcasieu Parish in 2015 (Louisiana Department of Natural Resources, written commun., 2015).

	Shallow sand	"200-foot" and upper sands	"500-foot" sand	"700-foot" and lower sands	Undifferentiated sand
Domestic	276	2,985	935	15	20
Industrial	5	35	121	12	4
Irrigation	17	120	93	16	7
Public supply	7	142	120	13	4
Power generation	0	0	6	0	0
Total	**305**	**3,282**	**1,275**	**56**	**35**
Well depth range (feet below land surface)	13–305	18–590	130–740	445–849	70–460
Yield range (gallons per minute)	2–50	4–5,471	5–5,000	20–4,700	30–4,000

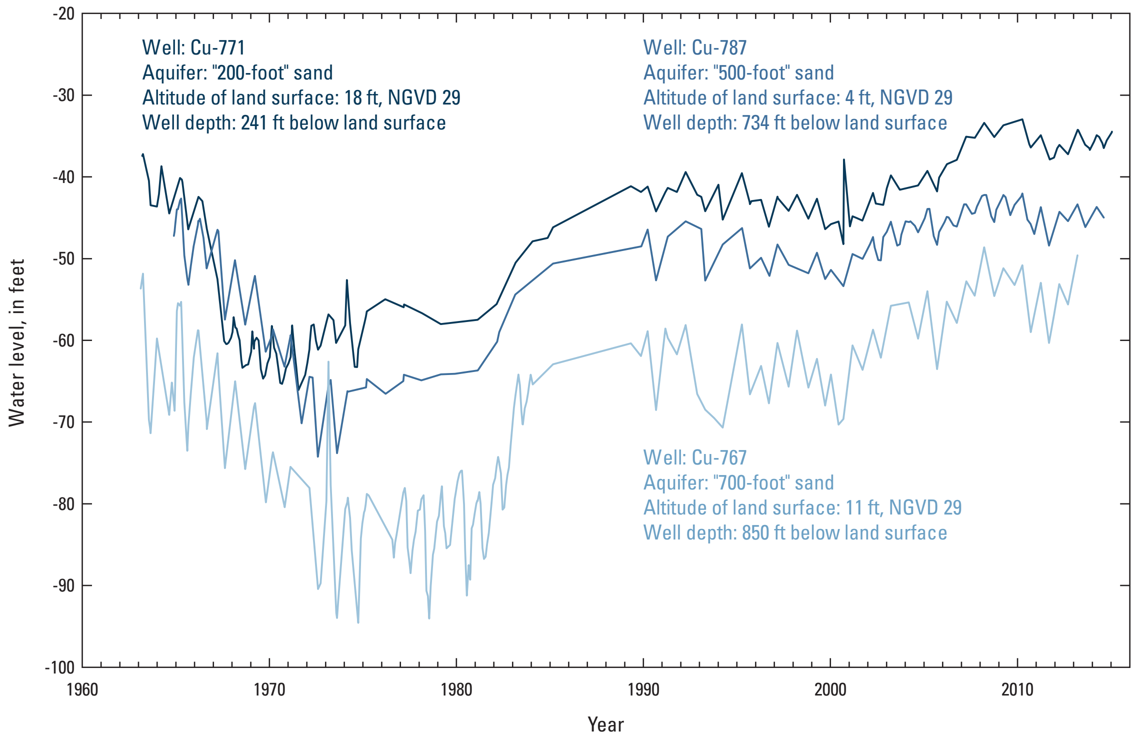

Figure 4. Water levels in wells Cu-771, Cu-787, and Cu-767 screened in the "200-foot" sand, "500-foot" sand and "700-foot" sand of the Chicot aquifer system in Calcasieu Parish, Louisiana (see fig. 1 for well locations; U.S. Geological Survey, 2016a). Land surface and water levels are in feet (ft) relative to the National Geodetic Vertical Datum of 1929 (NGVD 29).

"500-foot" sand, saltwater is present along much of the southern parish boundary, in the southeastern corner of the parish, and in three small isolated areas at or near industrial facilities between Lake Charles and Sulphur. At the base of the "700-foot" sand and in the lower sand, saltwater is present in the southern two-thirds of the parish. The "700-foot" sand contains only saltwater along most of the southern parish boundary (Harder, 1960; Nyman, 1989).

Surface-Water Resources

Surface-water resources in Calcasieu Parish are available in two regional drainage basins: the Calcasieu-Mermentau Basin (Hydrologic Unit Code [HUC] 080802), which covers the majority of the parish, and the Sabine Basin (HUC 120100), which is present along the Sabine River on the western side of the parish (U.S. Geological Survey, 2016b). In 2010, about 136.7 Mgal/d of surface water were withdrawn in Calcasieu Parish for public supply, industry, power generation, livestock, rice irrigation, and aquaculture use (table 2). Over 95 percent of surface-water withdrawals came from the Calcasieu River (76.22 Mgal/d) and Sabine River Diversion System (54.07 Mgal/d) (table 2).

Calcasieu-Mermentau Basin

The Calcasieu-Mermentau Basin is subdivided into six subbasins, four of which are present in Calcasieu Parish. These subbasins are the West Fork Calcasieu (HUC 08080205), Upper Calcasieu (HUC 08080203), Lower Calcasieu (HUC 08080206), and Mermentau (HUC 08080202) (fig. 1).

The West Fork Calcasieu and Upper Calcasieu subbasins cover most of the northern half of the parish and drain south into the Lower Calcasieu subbasin, which extends to and drains southward into the Gulf of Mexico. The West Fork Calcasieu subbasin is drained by the Houston River, West Fork Calcasieu River, Indian Bayou, and many other small streams. The Houston River and Indian Bayou are tributaries of West Fork Calcasieu River, which flows into the Calcasieu River just upstream of Lake Charles. The Upper Calcasieu

Table 4. Summary of selected water-quality characteristics of freshwater in the Chicot aquifer system in Calcasieu Parish, Louisiana (U.S. Geological Survey, 2016a).

[Values are in milligrams per liter, except as noted. °C, degrees Celsius; PCU, platinum cobalt unit; µS/cm, microsiemen per centimeter; SU, standard unit; $CaCO_3$, calcium carbonate; µg/L, microgram per liter; NA, not applicable; SMCL, Secondary Maximum Contaminant Level established by the U.S. Environmental Protection Agency (2016)]

	Temperature (°C)	Color, (PCU)	Specific conductance, field (µS/cm at 25 °C)	pH, field (SU)	Hardness (as $CaCO_3$)	Chloride, filtered (as Cl)	Iron, filtered (µg/L as Fe)	Manganese, filtered (µg/L as Mn)	Dissolved solids, filtered
“200-foot” sand of the Lake Charles area, 1940–2009 (111 wells)									
Median	22.0	1	483	7.5	110	32	230	140	280
10th percentile	20.3	0	364	6.9	66	16	30	60	232
90th percentile	23.3	10	1,090	7.9	200	120	2,800	450	509
Number of samples	79	28	95	68	73	106	46	48	63
Percentage of samples that do not exceed SMCLs	NA	93	NA	93	NA	100	59	6	86
“500-foot” sand of the Lake Charles area, 1940–2006 (239 wells)									
Median	23.5	5	404	7.2	110	34	1,000	350	258
10th percentile	22.0	0	301	6.8	80	22	180	240	214
90th percentile	25.0	20	677	7.6	140	98	2,200	480	436
Number of samples	127	99	188	143	155	237	97	91	104
Percentage of samples that do not exceed SMCLs	NA	87	NA	99	NA	100	19	1	92
“700-foot” sand of the Lake Charles area, 1939–95 (63 wells)									
Median	24.0	5	548	7.4	100	68	920	390	332
10th percentile	22.0	0	341	6.7	66	26	260	160	263
90th percentile	25.5	36	952	8.2	140	200	2,100	500	558
Number of samples	32	29	49	40	46	62	15	20	30
Percentage of samples that do not exceed SMCLs	NA	72	NA	92	NA	100	13	0	83
SMCLs									
	NA	15	NA	6.5–8.5	NA	250	300	50	500

subbasin is drained by the Calcasieu River whose tributaries include Bayou Serpent and many other small streams. The annual average discharge upstream of Calcasieu Parish for the Calcasieu River near Kinder (site number 08015500) (fig. 1) during 1922–2014 was 2,524 cubic feet per second (ft^3/s) (U.S. Geological Survey, 2016a) from a drainage area of 1,700 square miles (mi^2). The Lower Calcasieu subbasin in Calcasieu Parish contains the Calcasieu River, Bayou Choupique, the Gulf Intracoastal Waterway, and many other small streams. Multiple lakes are found along the Calcasieu River in Calcasieu Parish.

The Mermentau subbasin is located in the southeastern corner of the parish and is drained by Bayou Lacassine and other small streams.

Sabine Basin

The Sabine Basin contains only the Lower Sabine subbasin in Calcasieu Parish (HUC 12010005) and is drained by the Sabine River. The Sabine River drains a strip of land along the western border of the parish and is connected to the interior of Calcasieu Parish by canals. In the north-central part of the parish, the Sabine River Diversion System conveys water by way of canal from the Sabine River eastward to several industries located near Westlake and Sulphur. The system also supplies water for municipal use and irrigation (Sabine River Authority, 2007). In the southern part of the parish, the Gulf Intracoastal Waterway runs roughly east-west from the Texas border, across the Calcasieu River just south of Moss Lake, then southeastward into Cameron Parish. The annual average discharge of the Sabine River near Ruliff, Tex. (site number 08030500), (fig. 1) during 1961–2015 was 7,626 ft^3/s from a drainage area of about 9,330 mi^2 (U.S. Geological Survey, 2016a).

Surface-Water Quality

Water samples collected from the Calcasieu River near Lake Charles (site number 08015900) during 1968–78 and from the Sabine River near Ruliff, Tex., during 1967–2000 have median hardness values in the soft range (table 5). Over 80 percent of samples did not exceed the SMCL for iron concentrations, and median pH values were also within the SMCLs. Dissolved-oxygen concentrations were generally greater than 5 mg/L, which is considered the minimum value for a diverse population of fresh, warmwater biota, including sport fish (Louisiana Department of Environmental Quality, 2008).

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By Vincent E. White and Lawrence B. Prakken

For additional information, contact:

Director, USGS Lower Mississippi-Gulf Water Science Center
3535 S. Sherwood Forest Blvd., Suite 120
Baton Rouge, LA 70816
E-mail: gs-w-lmg_center_director@usgs.gov
Fax: (225) 298–5490
Telephone: (225) 298–5481
Home Page: http://la.water.usgs.gov

Table 5. Summary of selected water-quality characteristics for the Calcasieu and Sabine Rivers, Calcasieu Parish, Louisiana (U.S. Geological Survey, 2016a).

[Values are in milligrams per liter, except as noted. µS/cm, microsiemen per centimeter; °C, degrees Celsius; SU, standard unit; $CaCO_3$, calcium carbonate; µg/L, microgram per liter; SMCL, Secondary Maximum Contaminant Level established by the U.S. Environmental Protection Agency (2016); NA, not applicable]

	Specific conductance, field (µS/cm at 25 °C)	Oxygen, dissolved	pH, field (SU)	Hardness (as $CaCO_3$)	Calcium, filtered (as Ca)	Magnesium, filtered (as Mg)	Sodium, filtered (as Na)	Chloride, filtered (as Cl)	Sulfate, filtered (as SO_4)	Iron, filtered (µg/L as Fe)
Calcasieu River near Lake Charles, 1968–78[1]										
Median	98	7.4	6.7	18	4.2	1.7	12	18	6.0	140
10th percentile	43	5.4	5.8	10	2.5	0.8	4.3	5.1	3.7	80
90th percentile	3,360	10.0	7.2	330	26	65	520	980	130	360
Number of samples	49	48	49	49	49	49	49	49	49	15
Percentage of samples that do not exceed SMCLs	NA	NA	69	NA	NA	NA	NA	86	94	87
Sabine River near Ruliff, Texas 1967–2000[2]										
Median	142	7.8	6.8	29	7.4	2.4	15	18	12	150
10th percentile	92	6.4	6.2	18	4.9	1.3	9.2	11	7.2	70
90th percentile	197	10.2	7.2	38	10	3.3	21	27	19	360
Number of samples	538	190	302	291	291	291	213	520	519	106
Percentage of samples that do not exceed SMCLs	NA	NA	80	NA	NA	NA	NA	100	100	87
SMCLs										
	NA	NA	6.5–8.5	NA	NA	NA	NA	250	250	300

[1]Site number 08015900 (see fig. 1).

[2]Site number 08030500 (see fig. 1).

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ABANDONED OIL AND GAS INDUSTRY WELLS AND THEIR ENVIRONMENTAL IMPLICATIONS

UIPC SUMMER MEETING

Proceedings

Portland, Oregon
MARRIOTT HOTEL
July 31 - Aug. 3, 1988

UNDERGROUND INJECTION PRACTICES COUNCIL

1988 SUMMER MEETING

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UIPC/UIPC Research Foundation Headquarters
525 Central Park Drive
Suite 304
Oklahoma City, OK 73105

(405) 525-6146

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Prepared by

Dr. Don L. Warner, P.E., C.P.G.
Rolla, Missouri

for the

American Petroleum Institute
Washington, D.C.

February 1988

CONTENTS

ABANDONED OIL AND GAS INDUSTRY WELLS AND THEIR ENVIRONMENTAL IMPLICATIONS

FIGURES

I. SUMMARY AND CONCLUSIONS

Many thousands of wells have been drilled and abandoned during the 130 year history of the U.S. petroleum industry. Regulations for plugging of such wells were nonexistent in the early days of the industry and have evolved, over the years, to their present effective level. Thus, an unknown but large number of abandoned wells exist that are unplugged or inadequately plugged by today's standards.

As a result of incidents in which abandoned wells have been implicated as sources of ground water contamination, such wells are often considered, without discrimination among them, to be potential pathways for contamination of an underground source of drinking water (USDW). Such contamination can result from interaquifer flow of natural formation water or by transmission of injected fluids from the injection reservoir to an USDW.

In fact, the relative contamination potential of such wells ranges from highly likely to impossible, depending on a complex set of geologic and hydrologic circumstances. The relative contamination potential of an abandoned well or wells in a particular geologic and hydrologic setting can be analyzed qualitatively by an understanding of the factors involved and can be quantitatively analyzed with available numerical computer models. An example of such a model analysis is given for a case where the abandoned well is judged to not be a potential source of contamination to an USDW, even in the presence of a nearby injection well.

It can be concluded that abandoned unplugged or improperly plugged wells may or may not pose a potential for contamination to underground sources of drinking water, depending on a complex set of geologic and hydrologic circumstances. Therefore, it seems reasonable that regulation of oil and gas industry activities should take into account the wide range of contamination potential of individual abandoned wells when establishing specific operating restrictions in their vicinity.

II. INTRODUCTION

During the 130 year history of the U.S. petroleum industry hundreds of thousands of oil and gas[1] exploration and production wells have been drilled, many of which are abandoned. For many years, effective requirements for the plugging of wells upon abandonment did not exist and, thus, an unknown but very large number of unplugged or inadequately plugged wells exists in the country. Such abandoned wells have been observed to be conduits by which

1. Under the Underground Injection Control regulatory programs of the U.S. EPA, petroleum industry injection wells are defined as Class II wells.

natural formation waters and, perhaps, injected fluids have migrated between subsurface formations (Figure 1) and in some cases, to the ground surface (Figure 2). This is a particular threat where injection wells are present that increase reservoir pressures and can induce such fluid movement as is shown in Figures 1 and 2.

As a result of such known or suspected incidents involving abandoned wells, some can be expected to believe that all abandoned wells pose a contamination potential to USDW's. This paper is intended to briefly outline the circumstances under which abandoned unplugged or improperly plugged wells may and, on the other hand, may not be a pathway for contamination of an USDW. The paper will show that the circumstances that determine the extent of hazard of an abandoned well are very complex and have, only recently, become subject to analysis by computer modeling. A case example of such modeling is given in which an abandoned well is analyzed and judged to not be a threat to an USDW.

III. GEOLOGY AND HYDROGEOLOGY OF OIL AND GAS PRODUCING REGIONS

A. General Geologic Frameworks

The vast majority of oil and gas production is from sequences of sedimentary rocks that occur in geologic basin areas and range in thickness from a few thousand to over 50,000 feet. Oil and gas wells that penetrate these sedimentary rocks range from several hundred to over 20,000 feet in total depth. Types of sedimentary rocks containing oil and gas include sand and sandstone, siltstone, shale, limestone, dolomite, salt, gypsum and, occasionally, other less common ones. Sand, sandstone, limestone and dolomite are commonly porous and permeable enough to act as oil and gas producing reservoir rocks whereas siltstone, shale salt and gypsum are more likely to act as cap rocks or confining beds.

The various sedimentary rock types occur in intercalated sequences, depending on the environment in which they are deposited and the nature of the supply of the depositional material. In the United States, particular geologic basins are characterized by the rock sequences that they contain. For example, the Texas-Louisiana Gulf coastal region contains principally interbedded sand-siltstone-shale, whereas various interior basins are dominated by carbonate (limestone and dolomite) rocks with occasional sandstones and shales. These consolidated to semiconsolidated oil and gas bearing rocks are from Cambrian to Tertiary in age.

In many areas, the sedimentary rocks described above are overlain by thin layers of unconsolidated gravels, sands, silts and clays of alluvial, glacial or other origin that are of Recent or Pleistocene age and are generally fresh-water bearing.

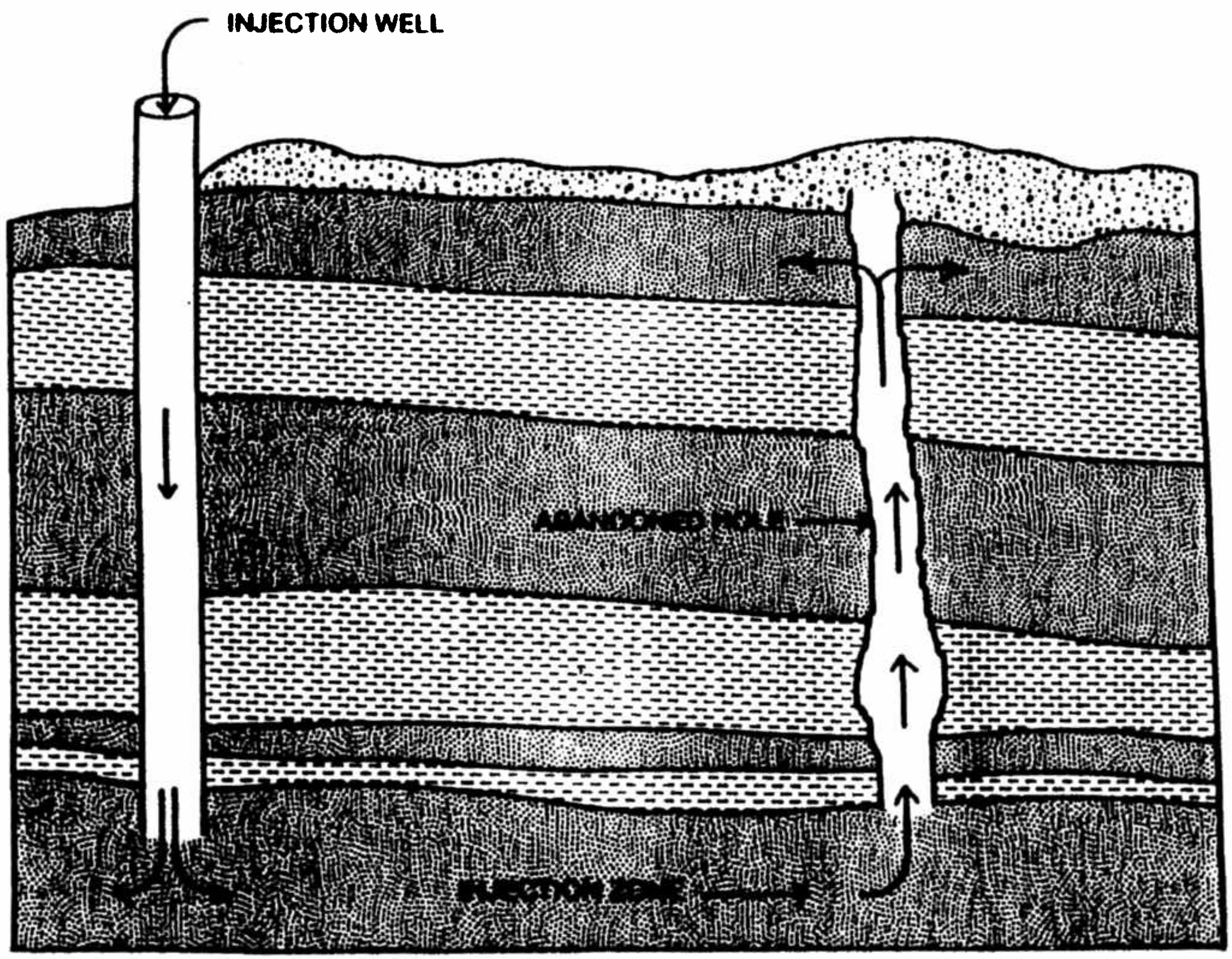


Figure 1 - Schematic diagram of interaquifer flow through the borehole of an abandoned well (Aller, 1984).

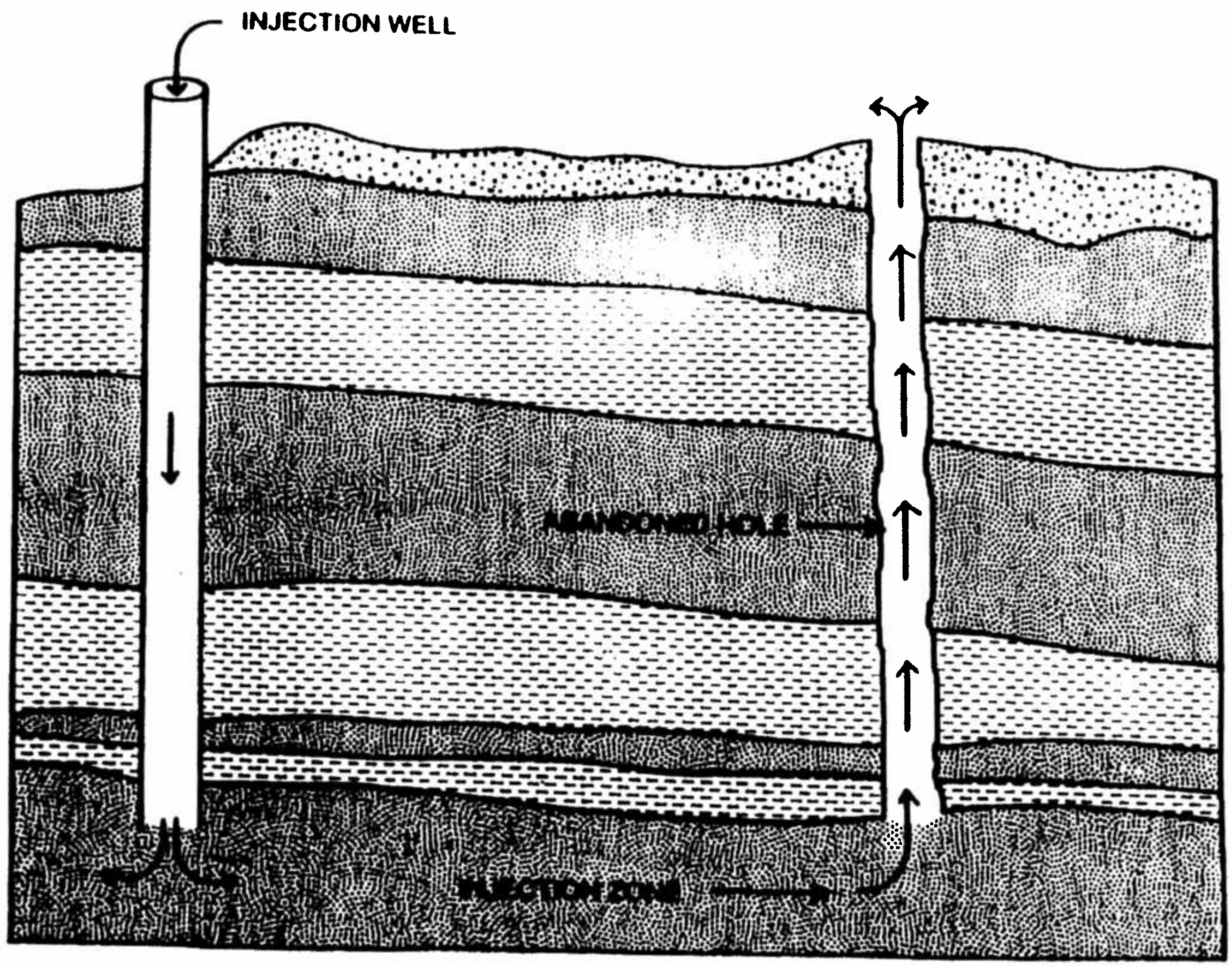


Figure 2 - Schematic diagram of flow to the ground surface through the borehole of an abandoned well (Aller, 1984).

B. Groundwater Occurrence and Movement

All soils and rocks contain water, in the subsurface. At depths of from a few feet to, at most, a few hundred feet, there is sufficient water present to completely saturate the soil or rock. The depth, at which saturation occurs is termed the ground-water table. Below that depth, all soil or rock is saturated and the contained water is termed ground water. Shallow ground water is often unconfined, that is, precipitation is able to infiltrate directly to the water table and recharge the water-containing aquifer. At greater depths, ground water becomes confined or semiconfined by the less permeable rocks in the sedimentary sequence. Oil and gas occurs and is accumulated in deep confined aquifers or reservoirs in very limited locations where structural and stratigraphic geologic conditions are favorable. All of the remaining subsurface rocks are entirely water filled.

Ground water circulates in response to the hydrologic cycle of precipitation, infiltration, recharge, ground water flow and discharge. Shallow ground water may flow relatively rapidly, as much as several feet per day, whereas very deep confined ground water may be almost stationary, flow rates being so slow as to be unmeasurable with the methodology available and in the time framework in which man operates.

In areas of relatively gentle topography, water in confined aquifers at the location of a single drilled well would rise in that well to nearly a common elevation, when adjusted for the differing density of the water in different aquifers. This condition is referred to as hydrostatic and simply means that there is little or no potential for the water to move vertically from one confined aquifer to another. In other cases, vertical equilibrium does not, naturally, exist and flow is occurring, though usually slowly, among confined aquifers. The status of the local ground water system, hydrostatic or not, is determined by drilling a borehole and measuring the level of the piezometric surface in each successively deeper aquifer by one or more of the various measurement methods available.

C. Groundwater Chemistry

The chemical quality of natural ground water is characterized by its content of the common cations, sodium, potassium, calcium and magnesium and the common anions; chloride, bicarbonate and sulfate and by the total dissolved solids comprised by these constituents. Fresh waters contain up to 1,000 mg/l of TDS, brackish waters 1,000-10,000 mg/l, saline waters 10,000-100,000 mg/l and brines greater than 100,000 mg/l of TDS.

The salinity or TDS content of a ground water is determined by its age and location and by the minerals that it has contacted during its lifetime. Young shallow waters tend to be low in TDS and deep old waters high in TDS. Often, a progressive increase in salinity occurs, with depth, in the aquifers intersected by a borehole in an oil producing area. Increased salinity also means increased density. Fresh water weighs

62.4 lb/ft^3 (has a specific gravity of 1.0) whereas a brine with a TDS content of 100,000 mg/l will weigh about 66.5 lb/ft^3 and have a specific gravity of 1.066. The hydrostatic pressure gradient of the fresh water would be 0.433 psi per foot of depth and of the brine would be 0.469 psi per foot of depth. An "average" hydrostatic gradient might be about 0.46 psi per foot of depth.

D. Hydrogeologic Parameters

To make quantitative assessments of ground water flow patterns and any consequent transport of contaminants in the subsurface, it is necessary to measure or estimate a number of hydrogeologic parameters or characteristics of the fluids and rocks involved. Fluid properties are density, viscosity compressibility and chemistry. Rock properties includ porosity, permeability, thickness and compressibility.

These fluid and rock properties are obtained by a variety of geologic, geophysical and engineering methods or, where not measured, are estimated. Calculations are then made with analytical equations or numerical models to analyze and predict patterns of subsurface water flow and possible associated ground water contamination.

IV. ENVIRONMENTAL IMPLICATIONS OF ABANDONED WELLS

When a borehole is drilled through a series of subsurface geologic formations that contain waters of differing chemical quality, it immediately becomes a potential pathway for movement of those waters among formations. This is one reason why wells are cased with steel casing and why cement is forced into the open area (annulus) between the casing and the wall of the borehole. It is the principal reason for the careful plugging of well bores with cement and drilling mud before well abandonment.

A. Properly Plugged and Abondoned Wells

In recent years, the Federal Government and the states have adopte increasingly stringent requirements for the methods and procedures for plugging and abandonment of oil and gas wells. It is assumed that, whe wells have been plugged and abandoned under current procedures, the wel bores are sealed and do not allow movement of fluids among subsurface formations and, thus, are not potential sources of ground water contamination.

B. Improperly Plugged and Abandoned Wells

During the early history of the oil and gas industry, the potentia danger to usable ground water from abandoned unplugged or improperly plugged oil and gas wells was not recognized and many thousands of such wells were either not plugged at all or were inadequately plugged to prevent interformational water flow. In the earliest days of the oil and gas industry, scant or no recording requirements existed and the numbers and locations of many wells abandoned during that era are unknown.

As regulation improved, well permits were required and numbers and locations are on record. The details of plugging are, however, still often unknown and it must be assumed that effective plugs were often not emplaced. Modern wells are required to have permits for drilling and for abandonment and plugging methods and procedures are carefully supervised so that abandoned plugged wells are not a hazard to ground water.

From this brief history, it can be concluded that the potential for contamination to an USDW from abandoned wells is closely related to the era during which they were constructed, the hazard being from wells drilled prior to enactment of effective plugging and abandonment regulations. An important aspect of this conclusion is that the depth to which wells are drilled has steadily increased with time. Early wells were very shallow, often only a few hundred feet but seldom more than 2,000-3,000 feet in depth. Few wells today are less than 3,000 feet in depth. This means that most wells being drilled today will not be in direct conmmunication with many older unplugged or improperly plugged wells.

1. Exploration Wells vs. Development Wells

It is useful to distinguish among the types of wells drilled by the oil and gas industry when considering their possible contamination potential. Exploration wells are drilled outside of producing fields or are drilled to targets deeper than known production in producing fields. In either case, they are of lesser environmental concern than development wells drilled inside producing areas, since well density will be less and there is, therefore, less possiblity of interaction among wells that would lead to interformational fluid flow.

2. Variables Affecting Contamination Potential of an Abandoned Well

The variables that determine the contamination potential that an abandoned unplugged or improperly plugged well poses to underground sources of drinking water are many and complex. Let it first be said that some such abandoned wells do pose a threat to USDW's while many are believed not to, for reasons that will be examined.

a. Pressure Status of the Geologic Sequence Penetrated

In considering the potential environmental effects of unplugged or improperly plugged abandoned wells it is essential to characterized the pressure regimes that may exist in the formations penetrated by such wells. The possible detailed scenarios are too extensive for it to be practical to attempt to discuss them all. It was mentioned earlier that reservoirs or aquifers in a geologic sequence may naturally be under hydrostatic or normally pressured conditions or may be overpressured or underpressured relative to hydrostatic conditions. Considerable debate exists over the reasons for these varying natural pressure conditions but there is no question of their existence. Superimposed upon these natural reservoir or aquifer pressure conditions are the effects of petroleum production, groundwater pumpage, oilfield brine disposal by reinjection, secondary and enhanced oil recovery projects and other man-induced effects.

Whatever the original pressure status of a gelogic sequence of aquifers and reservoirs, petroleum production will lower the original pressure of the producing reservoir so that it will often be underpressured relative to the rest of the sequence. When petroleum production ceases, the reservoir will begin to return to its original natural pressure status. The rate of this pressure recovery depends upon the geologic and engineering reservoir characteristics but should require a time period comparable to that during when the reservoir was produced. The cycle of pressure depletion and recovery of an oil field will be affected by oilfield brine reinjection for pressure maintenance by waterflooding for secondary oil recovery and by enhanced-oil-recovery projects. Ground water pumpage will affect the pressures in drinking water aquifers similarly to production of petroleum reservoirs as described above.

The variety of possible flow patterns that can occur among aquifers and reservoirs with differing pressure conditions is, thus, very extensive and the local circumstances will have be examined in order to reach a conclusion concerning the threat of an abandoned well to an USDW. For example, there is no hazard of flow from a pressure-depleted petroleum reservoir to a normally pressured water-supply aquifer. In fact, flow would be into the pressure-depleted reservoir rather than from it. Even when reservoir pressure has recovered, no threat would exist in a normally pressured sequence. A hazard only exists when a saline-water bearing aquifer or reservoir is at a higher flow potential than an overlying fresh water aquifer connected with it by an unplugged or improperly plugged abandonded well. Even in that circumstance, movement of saline water into an USDW may not occur for reasons that will be describe below.

b. Abandoned Well Flow Mechanics

Given the presence of an abandoned well that is improperly plugged or unplugged, is open to a geologic sequence of aquifers and which penetrates a petroleum producing reservoir or reservoirs, the analysis of the potential for flow of natural saline water or injected fluids into underground sources of drinking water is a complex but tractable problem. Among the variables of the problem are:

i. Flow potential status of all aquifers and reservoirs in the sequence penetrated by the abandoned well. This is discussed under a. above.

ii. Status or condition of the borehole of the abandoned well - Even though a well may have not been plugged or may have been inadequately plugged at abandonment, most boreholes will contain impediments to interaquifer fluid flow. These include drilling muds, partially effective cement or mud plugs, collapsed or sloughed formations, formations that have expanded into the borehole and, possibly, drilling equipment or well completion equipment lost in the hole. Only under unusual circumstances will abandoned wells not contain such flow impediments. A possible case of that type would be a cable-tool well drilled in a sequence of competent strata in which drilling mud was not used and in which no form of plug was ever employed. Such wells probably exist in early field areas in several geologic provinces but will, typically, be shallow and not in communication with present producing formations. Probably all rotary drilled wells will contain, at least, drilling mud as a flow impediment.

iii. Details of the operation of petroleum or water producing activities in formations intersected by the borehole - The effects of any injection and/or production wells that are completed in formations intersected by the boreholes of an abandoned well must be superimposed upon the flow gradients that exist under non-operational conditions. For example, if an abandoned well is bottomed in a petroleum reservoir that is undergoing waterflooding, the pressure effects of waterflood injection and production wells at the point where the abandoned well penetrates the reservoir must be determined so that the total differential pressure available to move fluids up the abandoned well is known. Effects of pumping from or injection into other aquifers must also be accounted for. For example, pumping from a fresh-water bearing aquifer would create a pressure decrease that would encourage fluid movement into that aquifer.

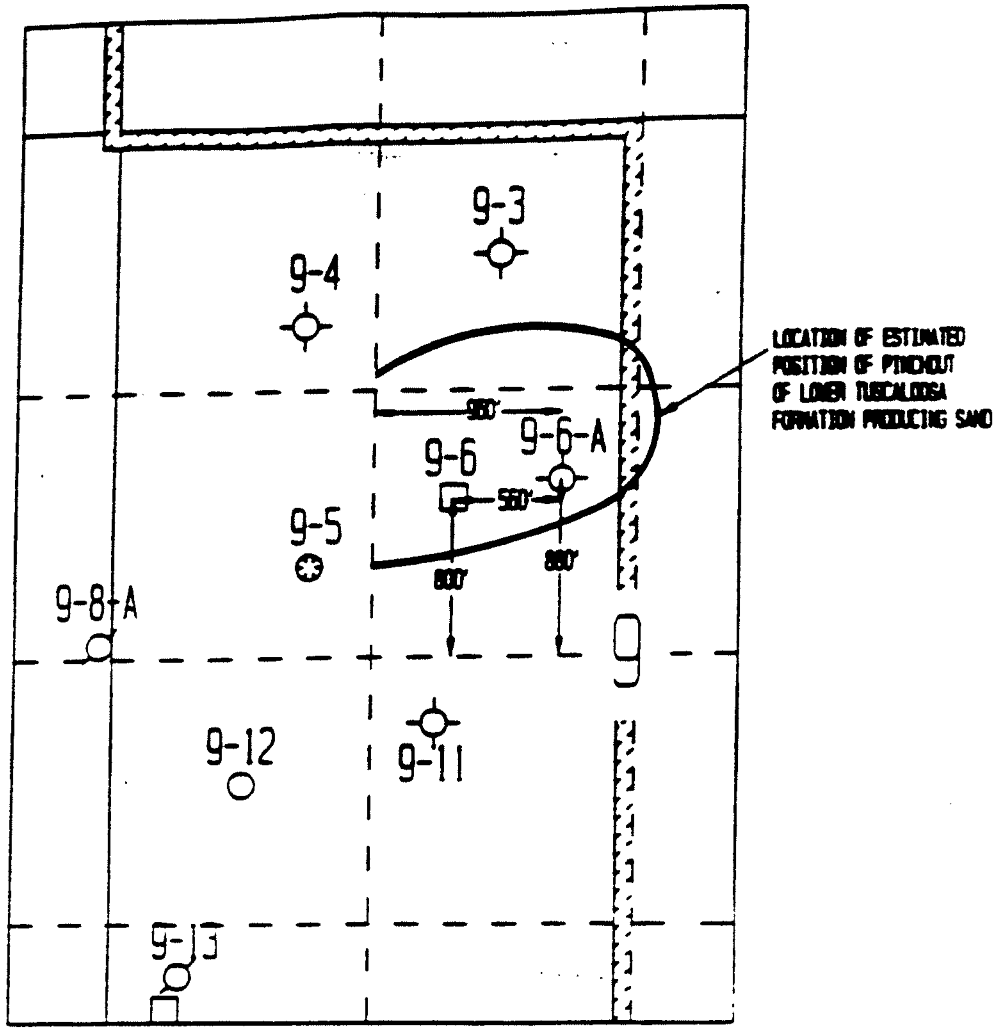
iv. Subsurface geologic conditions - Essential to determining the environmental hazard potential of an abandoned well is the subsurface geologic framework in the vicinity of the well. For example, if the abandoned well is drilled through formations that exhibit extreme lateral variability, the well may not be an effective pathway for fluid movement from an oil producing formation into a fresh water aquifer because the well may miss either t petroleum producing or water yielding units in the respective formations.

v. Engineering characteristics of all units in the geolog sequence and their contained fluids - The rate of flow and flow path that will be taken by formation waters o injected fluids in response to flow gradients that exi among formations in communication through an abandoned well will depend on the engineering properties of the formations and their contained fluids. Formation properties include porosity, permeability thickness an compressibility. Fluid properties include density, viscosity and compressibility. Both formation and flu properties and the differential flow gradient are ente into the appropriate analytical equations or numerical models in order to calculate flow paths and flow quantities. Such calculations are an accepted means c modeling subsurface flow problems and provide relative practical means of evaluating hazard of an abandoned well.

V. CASE EXAMPLE

The case example that will be described is based on a recent unpublisl study of the possible environmental effects of an abandoned well located n a proposed water injection well. The wells are located in an oilfield undergoing an enhanced oil recovery project in Mississippi. Figure 3 show portion of the oilfield with the two wells studied. Well 9-6 is the propo water injection well. Well 9-6A is the abandoned well. The producing san for the oilfield pinches out by facies change to the north, east and south the two wells, as shown in Figure 3. Figure 4 shows a generalized stratigraphic column for the field. The Lower Tuscaloosa Sand is the producing sand for the field. It occurs at a depth of 10,490 feet in well and is 26 feet thick. The base of the deepest underground source of drink water occurs at a depth of 3100 feet, in sands of the Sparta Formation, wh is about 700 feet thick.

The predicted hydraulic effects in abandoned well 9-6A resulting from proposed injection into Well 9-6 were studied with a numerical model, SWIF III (Ward, 1987). SWIFT III is a revised and improved version of a code originally developed for the U.S. Geological Survey specifically for inje well modeling. The original code and its successors have received extens verification, validation and use. Figure 5 depicts the finite difference used in the simulations. Figure 6 is another representation of the grid showing the line of cross-section A-A', which is used to display the resu of selected simulations.



XYZ FIELD
MISSISSIPPI

WELL STATUS
JULY 1987

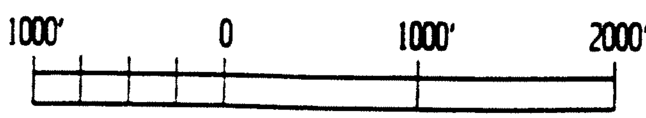
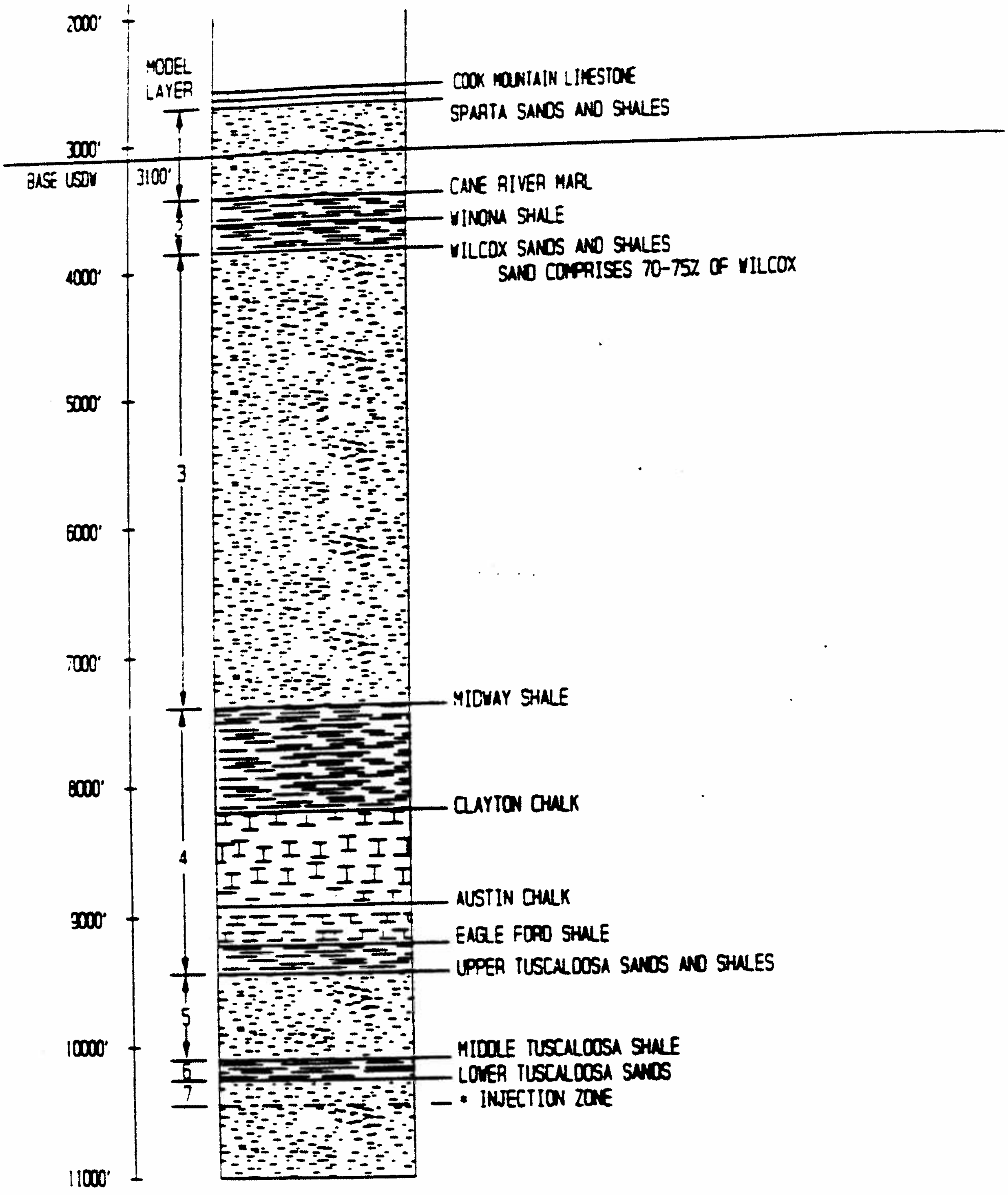


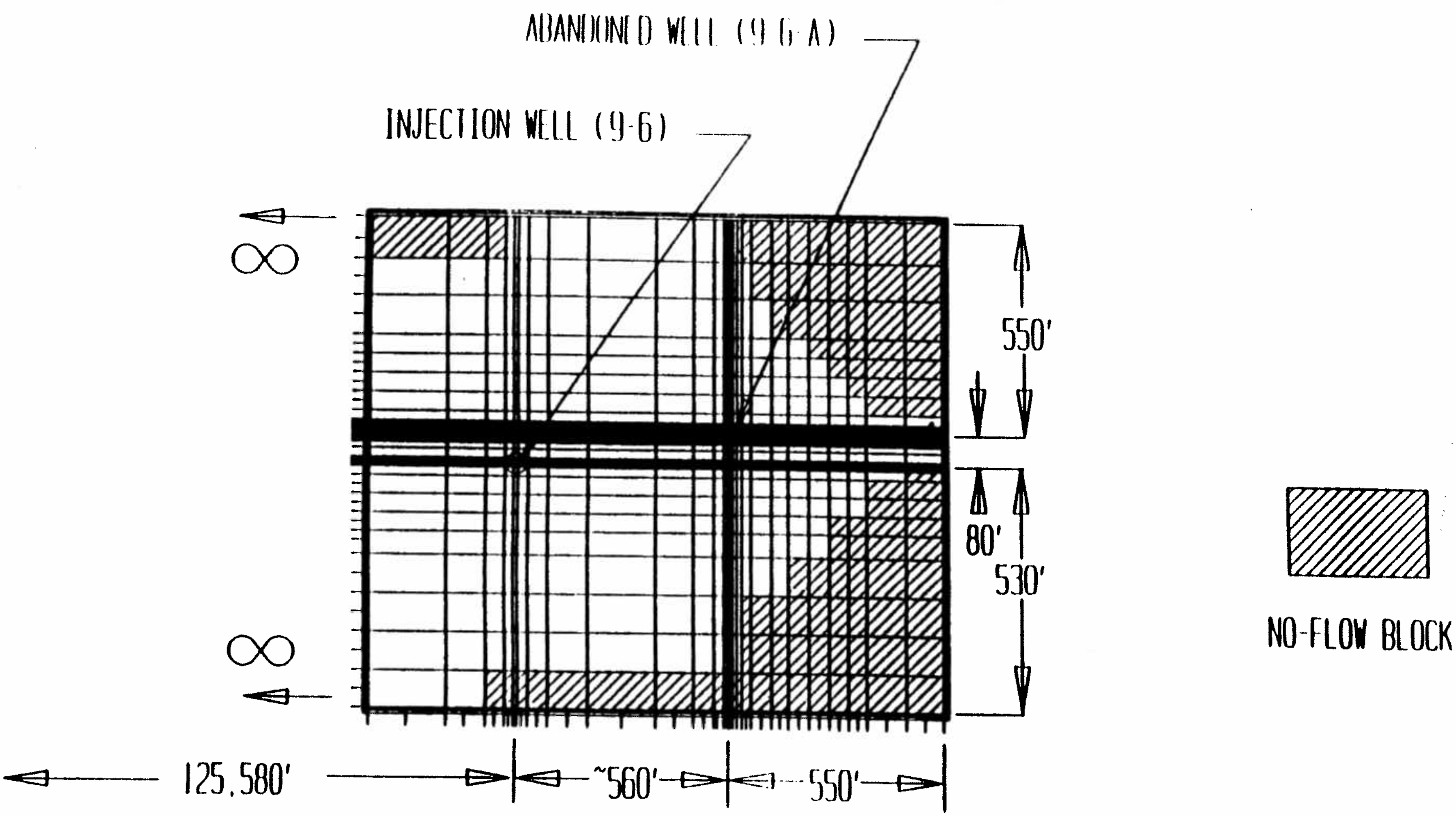
FIGURE 3

FIGURE 4

GENERALIZED STRATIGRAPHIC COLUMN

XYZ FIELD
MISSISSIPPI



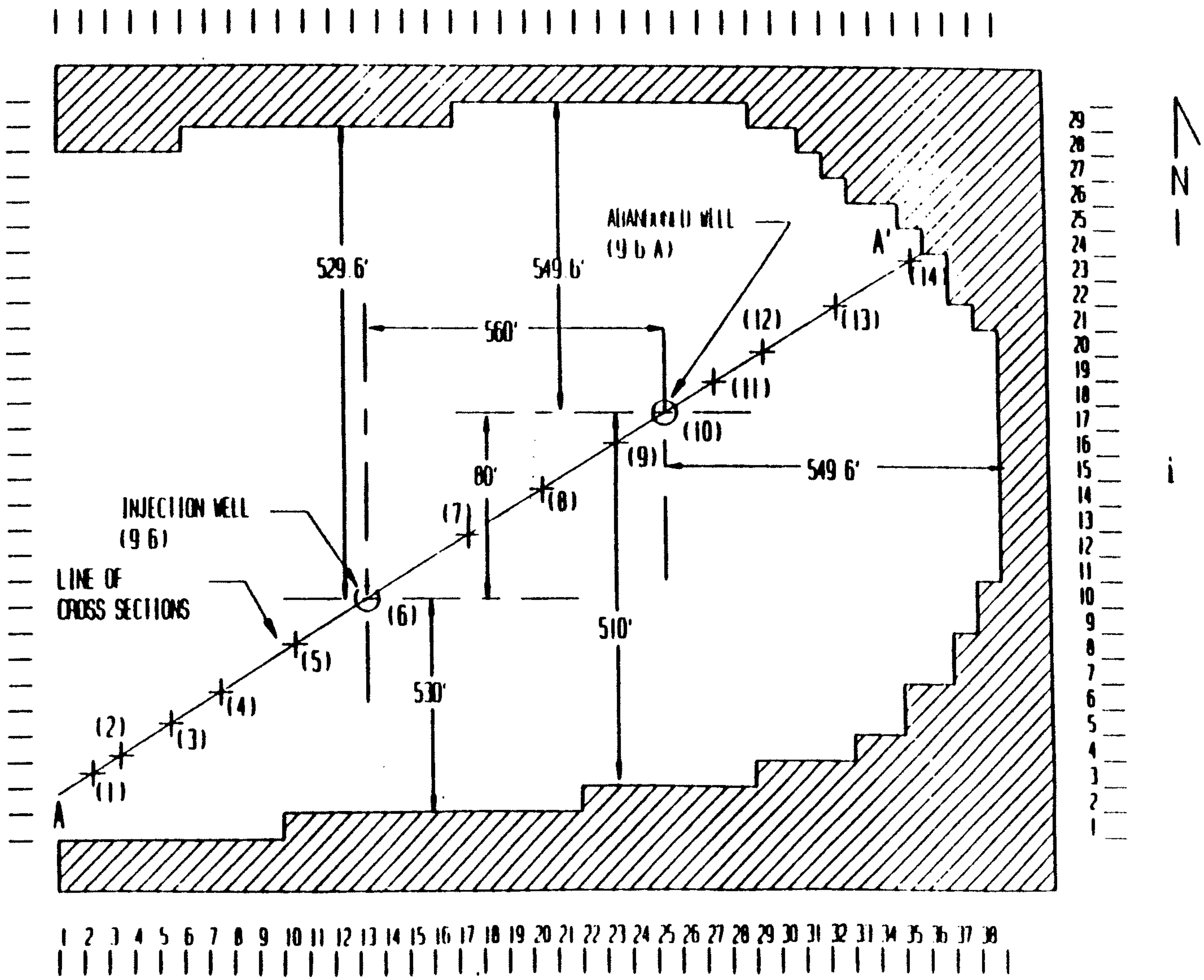


SCALED SIMULATION GRID

FIGURE 5

FIGURE 6

DETAIL OF THE SIMULATION GRID (7 LAYERS)



The energy company that operates the oilfield under study provided the geologic and engineering parameters and operating schedule for Well 9-6, needed as input to the numerical model. It was assumed that the injection well would operate at near its maximum injection capacity, the constraint being the local fracture gradient of about 0.7 psi per foot of depth. The permeability of the Lower Tuscaloosa Sand was assumed to be a maximum probable 30 millidarcys and a minimum probable 2 millidarcys. The large range is the result of uncertainty concerning the effect of residual oil on the permeability to water. A total of about 20 simulation runs were made to calibrate the model and 10 final simulations were run to test various borehole and reservoir conditions. The results of representative simulations are discussed below.

Figure 7 displays the results of a simulation in which the borehole of Well 9-6A was considered to be unplugged.[1] The Lower Tuscaloosa Sand was considered to have a permeability of 30 millidarcys and the injection rate in Well 9-6 considered to be 200 bbl/day. Reservoir pressure at the wellbore of Well 9-6 increased 908 psi over the 10-year simulation period and increased about 752 psi in the Lower Tuscaloosa Sand at the borehole of abandoned Well 9-6A. This pressure increase was transmitted through the Middle Tuscaloosa and through the borehole of Well 9-6A to the extent that up to a 7.2 psi pressure increase occurred in the Upper Tuscaloosa. Transmission of pressure through Well 9-6A also caused a buildup of up to 4.8 psi in Model Layer 4 but no pressure increase could be observed in the Wilcox Formation or units above the Wilcox. This result indicates that upward flow through abandoned Well 9-6A was insufficient to cause an observable pressure increase in the Wilcox and that no transmission of water to units above the Wilcox would be expected to occur. All subsequent simulations in which the permeability of the Lower Tuscaloosa Sand and the injection rate of Well 9-6 were proportionately varied, yielded the same result.

Cases were also studied where a plug composed of precipitated drilling mud solids was hypothesized to have developed. Figure 8 displays the results of one such simulation in which a plug of only 10-feet in length was considered to have developed in the interval of the Middle Tuscaloosa Formation. The 10-foot plug was assigned a permeability of 10^{-3} millidarcys. As shown in Figure 8, no observable pressure increase developed in layers above the Middle Tuscaloosa.

1. As has been discussed, it is believed that all rotary drilled boreholes will have some hydraulic resistance to flow. In this study, permeabilities of from about 40 to 4000 darcys were assigned to the borehole of Well 9-6A with no observable difference in the results.

FIGURE 7

INCREASE IN PRESSURE (PSI) ABOVE HYDROSTATIC ALONG SECTION A-A' AFTER 10 YEARS OF INJECTION

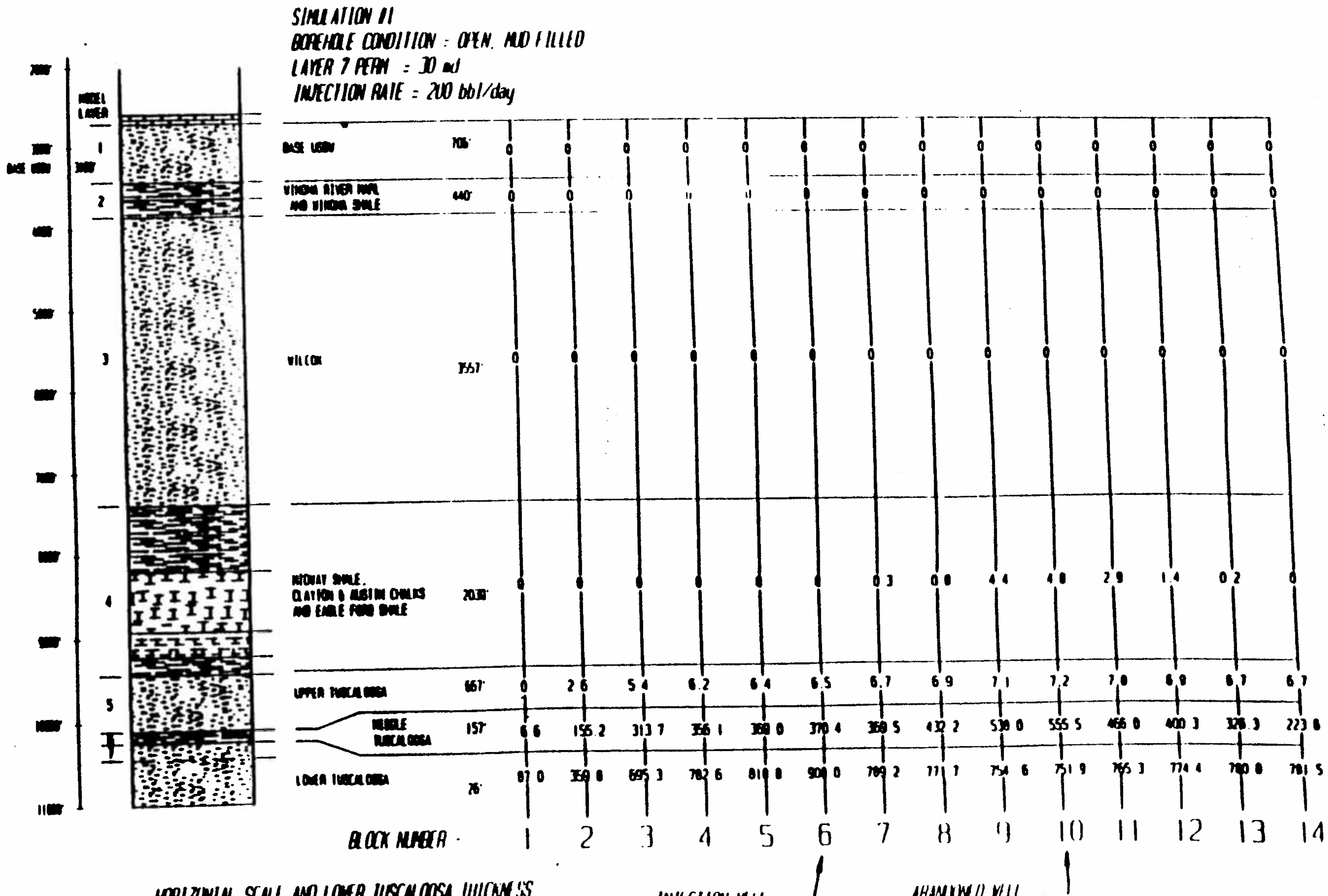
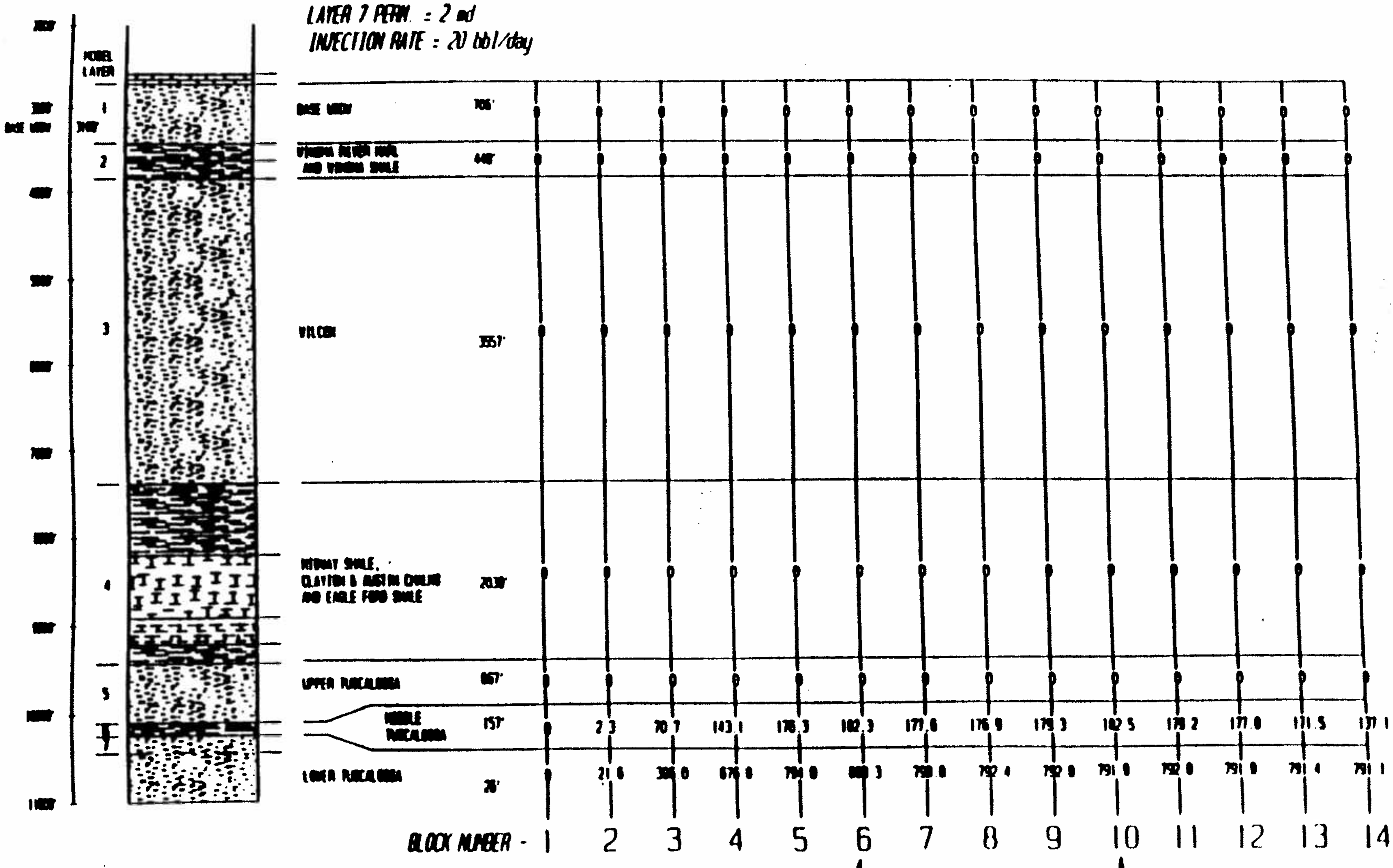


FIGURE 8

INCREASE IN PRESSURE (PSI) ABOVE HYDROSTATIC ALONG SECTION A-A' AFTER 10 YEARS OF INJECTION

SIMULATION #5
BOREHOLE CONDITION : 10 FT PLUG w/PERM. = 10' md
LAYER 7 PERM. = 2 md
INJECTION RATE : 20 bbl/day



INJECTION WELL

ABANDONED WELL

HORIZONTAL SCALE AND LOWER TUSCALOOSA THICKNESS ARE DISTORTED TO DISPLAY THE DATA

The conclusion of the example discussed here is that modeling indicates that abandoned Well 9-6A poses no threat to underground sources of drinking water even if the nearby Well 9-6 were to be used for water injection at rate of up to 200 bbl/day over a period of 10 years. It can be expected that similar studies in other geologic and hydrologic situations would show that, in many cases, abandoned wells probably pose no potential for contamination o an USDW under any reasonable set of assumed circumstances. Thus, a differentiation among abandoned wells is needed to identify those locations i which such wells require the close attention of industry and regulatory agencies and those locations where the contamination potential is low to, perhaps, nonexistent.

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CONFINING LAYER STUDY-SUPPLIMENTAL REPORT:

PREPARED FOR U.S. EPA REGION V

CHICAGO ILLINOIS

Confining Layer Study -

Supplemental Report

Prepared for

U.S. Environmental Protection Agency

Region V, Chicago, Illinois

SUBMITTED BY:

ENGINEERING ENTERPRISES, INC.

WATER RESOURCES SPECIALISTS

UNDER CONTRACT NO. 68-01-7011

CONFINING LAYER STUDY - SUPPLEMENTAL REPORT

PREPARED FOR U.S. EPA REGION V
UNDER CONTRACT NO. 68-01-7011

RESPECTFULLY SUBMITTED
DON L. WARNER, INC.
ROLLA, MISSOURI
ENGINEERING ENTERPRISES, INC.
NORMAN, OKLAHOMA

AUGUST, 1986

DISCLAIMER

Although the information in this document has been funded wholly or in part by the United States Environmental Protection Agency under Contract No. 68-01-7011 to Engineering Enterprises, Inc., it does not necessarily reflect the views of the Agency and no official endorsement should be inferred.

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Principal Authors :	Dr. Don L. Warner University of Missouri, Rolla
	Mr. Talib Syed Engineering Enterprises, Inc.
Contributing Author: (Chapter 5)	Dr. Stanley N. Davis University of Arizona, Tucson
EEI Project Manager:	Dr. Richard N. Tinlin Engineering Enterprises, Inc.
EPA Project Officer:	Mr. A. Roger Anzollin U.S. EPA, UIC Branch Washington, D.C.
EPA Work Assignment Manager :	Mr. Gary D. Harmon U.S. EPA - Region V Chicago, Illinois

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CHAPTER 9

FLOW THROUGH CONFINING LAYERS

The entire purpose of the evaluation of a confining layer or layers for containment of injected wastewater is to provide assurance against vertical migration of wastewater or saline water from the injection unit into overlying fresh water bearing aquifers. Such vertical movement could occur as a result of:

1. Intergranular flow through unbreached confining strata,
2. Flow through naturally fractured or faulted confining strata,
3. Flow through confining strata with solution porosity and permeability,
4. Flow through artificially fractured confining strata,
5. Flow through abandoned unplugged or improperly plugged wells.

Flow under each of these conditions is discussed below.

9.1 Natural Intergranular Flow

If the confining layer is a clastic sedimentary rock, that is, it is composed of discrete sedimentary particles and is unfractured, then fluid flow will be through intergranular spaces. Shales and siltstones and gradations between them are examples of such rocks. Flow through the intercrystalline spaces in chemically deposited rocks such as limestones is also intergranular flow.

Darcy's law for the flow of water through a granular rock is:

$$v = \frac{\bar{K} \Delta P}{\mu \Delta L} \tag{9-1}$$

where:

v = darcy velocity [cm/sec]

$\bar{K}$ = permeability [darcys]

μ = viscosity [centipoise]

ΔP = pressure differential across the flow distance [atmosphere]

ΔL = flow distance [centimeters]

Furthermore, the actual average intergranular liquid velocity is:

$$\bar{v} = \frac{v}{\phi_e} \tag{9-2}$$

where:

$\bar{v}$ = average intergranular velocity [cm/sec]

ϕ_e = effective porosity

The fluid pressure in a reservoir into which liquid is being injected is greatest at the injection well face and declines approximately logarithmically away from the borehole. The pressure will also vary with time, increasing as injection continues or declining if injection ceases or the rate is reduced. For purposes of illustration, however, a maximum constant pressure can be assumed to exist at the injection well in order to calculate the rate at which wastewater might be moving vertically through a confining layer. While Equation 9-1 is strictly correct only for horizontal flow, it can be used here for purposes of illustration, if ΔP is considered to be a pressure differential across the confining layer that was induced by fluid injection and where no cross-formational flow potential existed prior to injection. Using Equations 9-1 and 9-2, the values in Table 9-1 were, then calculated. Table 9-1 shows illustrative rates of movement expressed in feet/year, for a range of pressures and permeabilities. For these cases, the confining layer was assumed to be 100 feet thick, the effective porosity to be 10 percent and the viscosity one centipoise.

TABLE 9-1 Distance of vertical travel of injected wastewater in feet/year through a 100-foot-thick confining stratum with various permeabilities and injection-induced pressure gradients. The effective porosity was assumed to be 10 percent and the viscosity to be one centipoise.

	P (psi)			
K (darcys)	500	1,000	2,000	5,000
1×10^{-3}	114 ft/yr	228 ft/yr	456 ft/yr	570 ft/yr
1×10^{-5}	1.14	2.28	4.56	5.7
1×10^{-7}	1.14×10^{-2}	2.28×10^{-2}	4.56×10^{-2}	5.7×10^{-2}
1×10^{-9}	1.14×10^{-4}	2.28×10^{-4}	4.56×10^{-4}	5.7×10^{-4}

A vertical wastewater travel of 114 feet/year would probably be unacceptably high but the assumed permeability in this case (1×10^{-3} darcys) is at the upper end of values that one might encounter in a confining stratum, whereas a value of 1×10^{-9} darcys is at the other extreme. The travel rates shown in Table 9-1 are only meant to be illustrative and not comprehensive. Additional computations can be made, quite simply, if so desired.

No mention has, so far, been made of the chemical quality of water that might be forced to flow from the injection unit to an overlying aquifer by injection pressure buildup. If the vertical flow is within the radius of spread of wastewater in the injection unit, then the water that would initially enter the overlying aquifer would be from the confining stratum and that would eventually be followed by injected wastewater. Outside of the radius of spread of the wastewater, the water initially entering the overlying aquifer would be from the confining stratum eventually to be followed by natural water from the injection unit.

An example of the type of analysis described above was documented by Hickey (1984) for an injection well facility at St. Petersburg, Florida. The stratigraphic and hydrogeologic section for the St. Petersburg injection site is given in Figure 9-1. Injection was carried out during a period of 32 months beginning in September, 1979, to determine the impact of long-term injection. During the first year of the test, the mean injection rate was 2,750 gpm through a single well into injection zone C and by a postulated wellbore interconnection into injection zone B. Hickey (1984) calculated the vertical velocities in the semiconfining bed between injection zones A and B and also the pressures at various monitor well locations using analytical equations similar to those given here.

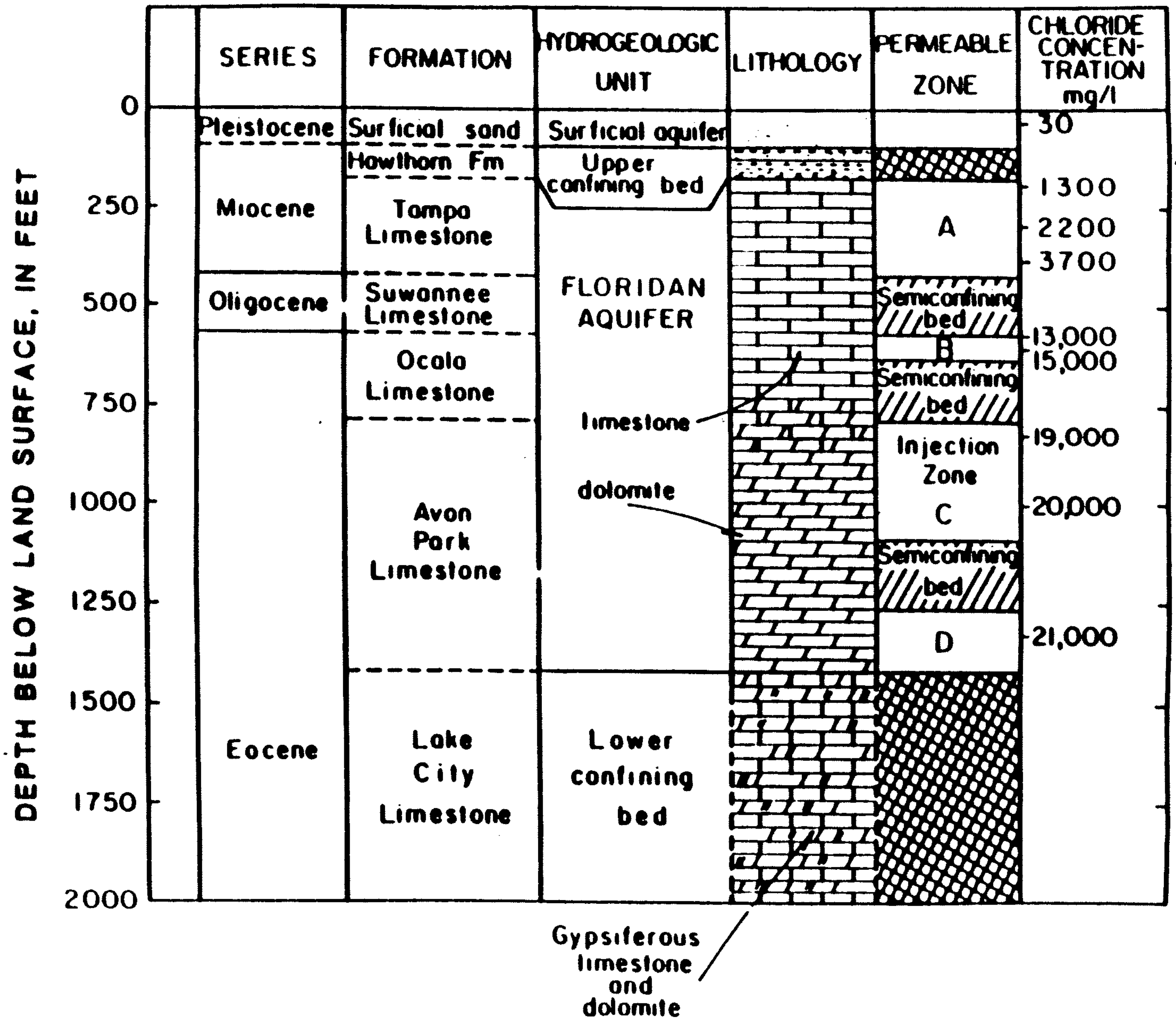

Figure 9-1 Stratigraphic and hydrogeologic section, St. Petersburg injection site (Hickey, 1984).

A much more powerful and revealing method of analysis, for a problem as complex as that at St. Petersburg, is the use of a numerical model such as the U.S. Geological Survey Saline Water Injection Program or SWIP (INTERCOMP Resource Development and Engineering, Inc., 1976). The SWIP model was used to obtain predicted pressures, vertical velocities and saline water displacements in the injection zones and semiconfining units at St. Petersburg for comparison with Hickey's (1984) results. Table 9-2 shows a comparison of pressures at selected monitoring points at the St. Petersburg injection well site as calculated by Hickey (1984) using analytical equations and as calculated for this study by use of the SWIP model. No field data were given by Hickey to allow comparison between observed and calculated pressures.

TABLE 9-2 Comparison of pressure buildups at observation well locations at St. Petersburg, Florida as calculated by Hickey (1984) and as calculated for this study using SWIP.

		Pressure Buildup	
Observation Well	Distance from Injection Well	From Hickey	From SWIP
A3	0	4	2.9
B6	45	1.6	2.5
B7	66	2.4	2
B8	100	0.5	1.0
B9	115	0.1	.08
B1	660	0.1	1.0
B2	660	0.1	1.0
B3	660	1	1.2
B4	660	1.4	1.3
B5	660	0.5	.3
C2	1300	0.8	.8
C3	1390	0.3	1.8

Figure 9-2 shows upward vertical velocities of pore water in the confining layer between injection zones B and A. The velocities are those computed by the SWIP model to exist after one year of injection at 2,750 gpm into zones B and C as explained above. For comparison, Hickey (1984) calculated velocities, using analytical equations, of 0.005 to 0.05 ft/day at a distance of about 733 ft. from the injection well and 0.01 to 0.1 ft/day immediately adjacent to the injection well. Figure 9-3 shows the calculated concentration fraction (C/C_0) of dissolved chemicals in zone A as forced upward from the semiconfining layer into zone A from injection into zone B. For example, if the semiconfining layer were to contain water with a chloride concentration of 13,000 mg/l (Figure 9-1), then the chloride concentration in the lower 20 feet of zone A would be increased by about:

$$(13{,}000 \text{ mg/l})\ (0.056) = 728 \text{ mg/l}$$

immediately adjacent to the injection well after one year of injection.

9.2 Naturally Fractured Strata

The effect of naturally occurring fractures in a confining layer is, commonly, to greatly increase the permeability and to create a secondary form of porosity which is small in magnitude but effectively interconnected. The net result is that wastewater transport through a fractured caprock may be tens or hundreds of times more rapid than through the same rock in the unfractured state.

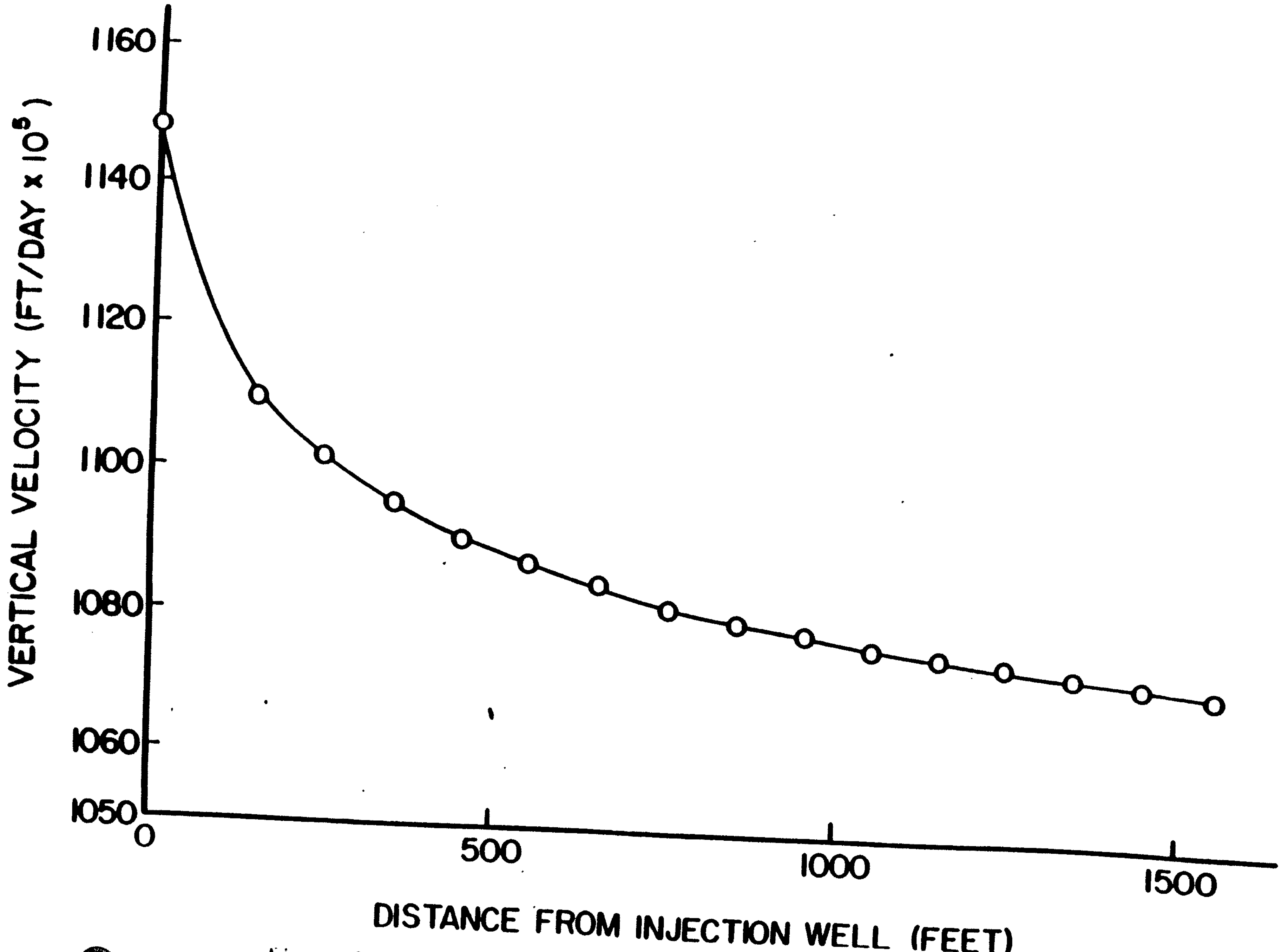

Figure 9-2 Vertical upward vel[illegible]s of pore water in the confining layer between injection [illegible]s A and B at St. Petersburg, Florida.

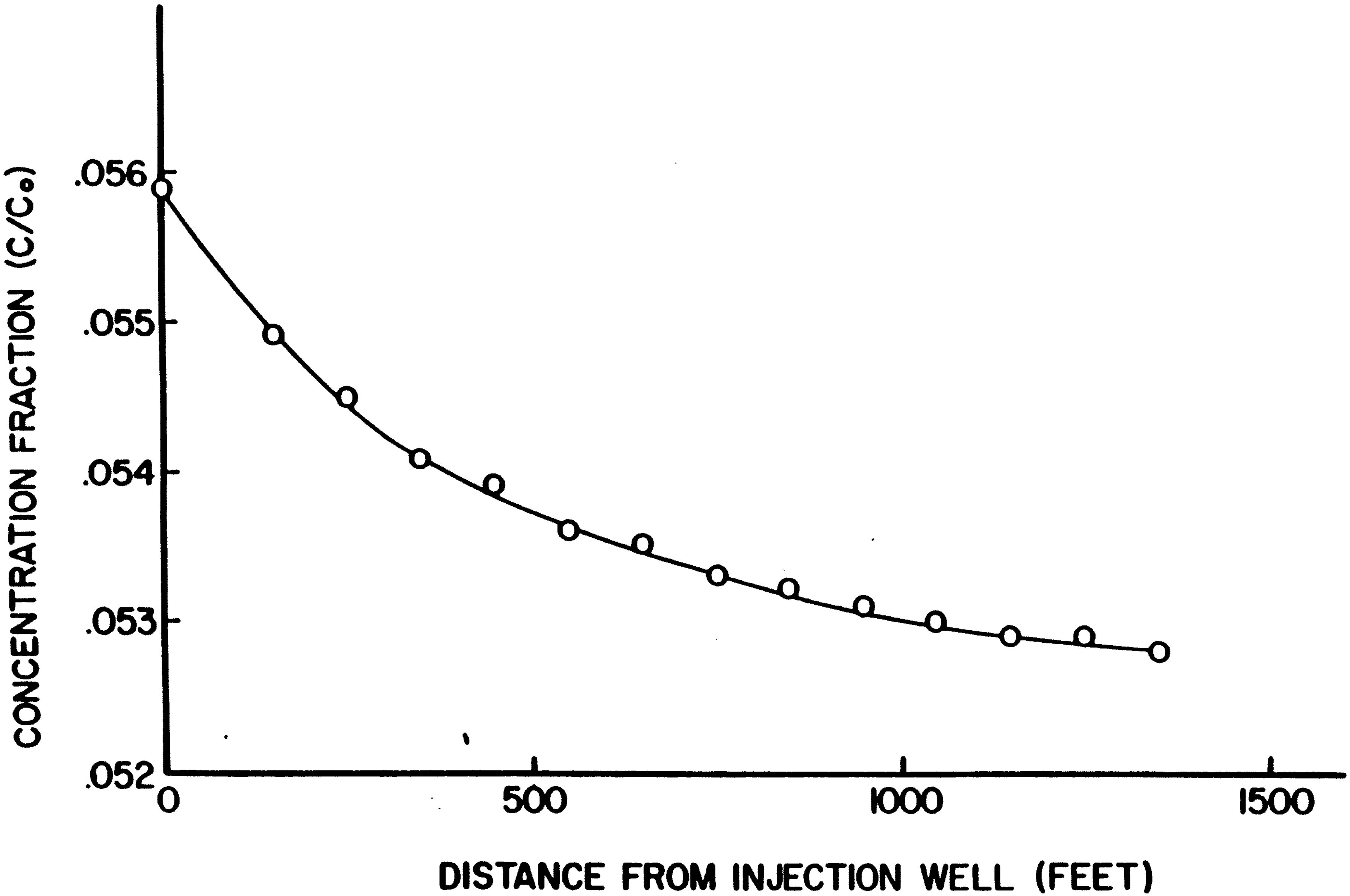

Figure 9-3 Concentration fraction C/C_0 of dissolved chemicals in zone A as forced upward from the semiconfining layer into zone A by injection into zone B at St. Petersburg, Florida

The analysis of flow through fractured rock is often treated no differently than flow through granular media. This approach is probably acceptable in many cases; but, where fractures are widely spaced, are of wide aperture or have a particular directional trend other mathematical methods may be needed (Freeze and Cherry, 1979, p. 73-74).

9.3 Strata With Solution Porosity

Solution porosity is often developed in conjunction with fractures and in soluble rocks and the above statements concerning fracture porosity will, thus, commonly be true where solution porosity exists.

9.4 Artificially Fractured Strata

Artificial fractures differ from naturally occurring ones in that they are more likely to be represented by a single vertical or horizontal fracture as opposed to a network of fractures. Also, if the artificial fracture has been deliberately induced, it will be propped open with sand, glass beads or other propping agents. Equations have been developed to predict fluid pressure distribution patterns in the vicinity of a well injection into single vertical or a horizontal fracture (Gringarten and others, 1974; Gringarten and Ramey, 1974). However, it is not likely that such equations would find application to the flow of fluid through a confining layer, since injection would be precluded if it were known that the confining layer was breached by an induced fracture.

9.5 Abandoned Unplugged or Poorly Plugged Wells

An abandoned, unplugged or poorly plugged well, penetrating the injection unit, within the radius of pressure influence of the injection well can act as a point leak from the injection unit to overlying aquifers. This is, of course, the main basis for the area of review determination required in the UIC regulations promulgated under the Safe Drinking Water Act.

While development of analytic equations to predict rates of interaquifer flow through a wellbore should not be particularly difficult, this has apparently not been done. However, work is currently in progress toward the formulation of analytic equations for this purpose in the Earth Sciences Division of the Lawrence Berkeley Laboratory, Berkeley, California (written communication P.A. Witherspoon, 1986).

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Correct size of reduction page numbers
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With a section on Quaternary Geology

By

Saul Aronow
Department of Geology
Lamar State College of Technology

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